Technical and Economic Feasibility of Biosolids-Amended Brick Production

By

George P. Yerousis

(1075105)

Supervisor

Dr. Eng. Rashed Al-Sa'ed

جامعة بيرزيت

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Birzeit University, 2010 - 2011

الجدوى الفنية والاقتصادية لصناعة الطوب الاسمنتي المعزز بالحمأة

جورج يروسيس

(1075105)

المشرف

د. راشد الساعد

BIRZEIT UNIVERSITY

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This thesis was prepared under the supervision of Dr. Rashed Al-Sa'ed and has been approved by all members of the Examination Committee.

Dr. Eng. Rashed Al-Sa'ed

(Chairman of the Committee) ....

Dr. Nidal Mahmoud

(Member) ....

Dr. Khaled Swaileh

(Member) ....

Contents

ABSTRACT

As stringent environmental control mandates are introduced and enforced, the traditional disposal routes of land application, land-filling, and incineration for processed biosolids will come under increasing pressure and may no longer be viable and cost-effective disposal outlets for sanitary engineers to capitalize on.

This Master thesis research investigates the technical viability of incorporating dehydrated biosolids and sewage sludge ashes into concrete raw material mixtures to produce pre-cast bricks that can be utilized in general-purpose outdoor building of non-load bearing structures. Furthermore, the cost-cutting benefits of producing such sludge-amended bricks are quantified.

The approach was to experiment with the addition of various sludge quantities to concrete mixtures – (making use of both sun-dried biosolids and sewage sludge ashes) - and then to evaluate and analyze the corresponding physical properties of the concrete mix paste and of the produced concrete bricks – mainly those properties affecting structural integrity. Results showed that there is a general inverse relationship between the amount of dried sludge or ashes added and the compressive strength development of the cured blocks. However, the addition of as much as 10% of biosolids' ashes to the raw ingredients of a concrete mix did not affect the general physical properties of concrete (i.e. the workability of the concrete mix and the compressive strength, water absorption, and density of the cured bricks). On the other hand, the addition of an equal quantity of sun-dried biosolids decreased the compressive strength of the cured concrete by about 20% - which can be attributed to the presence of the organic materials in the dried biosolids. Moreover, results showed that there is no significant change in the relative strengths of the tested concrete blocks when sludge is used in small quantities (i.e. 10% ashes or a combination of 2.5% dried biosolids and 7.5% ashes) as sand replacements in the concrete mixture.

For concrete bricks' manufacturers that utilize sand as a raw material ingredient in their production process, the incorporation of 10% sewage sludge ashes into concrete mixtures as a partial replacement for sand can achieve the highest possible monetary savings.

ملخص

مع تطور الأطر التشريعية البيئية وتزايد صرامة القوانين التي تكفل سلامة البيئة، فإن الخيارات التقليدية المستخدمة في التخلص من الحمأة الناجمة عن معالجة مياه الصرف الصحي مثل دفن الحمأة، أو حرقها (الترميد)، أو استخدامها في تخصيب الأراضي الزراعية ستواجه العديد من التحديات وربما لن يعد من المجدي اقتصادياً لمهندسي الصحة البيئية الإستمرار في تطبيق استخدام هذه الطرق التقليدية في إدارة التخلص من الحمأة.

يهدف هذا البحث الى دراسة الجدوى التِقنية لاستخدام الحمأة المجففة ورماد الحمأة المحروقة كمواد أولية في صناعة الطوب الاسمنتي المراد استخدامه في أعمال البناء الخارجية الخفيفة والجدران الغير حاملة للأوزان. كما تحاول هذه الدراسة حساب التوفير في تكاليف إنتاج الطوب الاسمنتي في حال استخدام الحمأة كبديل جزئي عن المواد الأولية التي تدخل في العملية الإنتاجية.

ولدراسة تأثير استخدام الحمأة في صناعة الطوب الاسمنتي، اعتمد البحث منهجية تقوم على تجربة إضافة كميات مختلفة من الحمأة المجففة ورماد الحمأة المحروقة الى المواد الأولية لخليط الخرسانة وتقييم وتحليل الخصائص الفيزيائية للخليط الخرساني وللطوب المتصلد ومقارنتها بخواص الخرسانة الخالية من الحمأة. وقد أظهرت نتائج الدراسة وجود علاقة عكسية ما بين كمية الحمأة أو رماد الحمأة المضافة الى خليط المواد الأولية ومقاومة الضغط للخرسانة المتصلدة. وبالرغم من ذلك، فقد تبين انه من الممكن اضافة رماد الحمأة المحروقة بنسبة ١٠% (من وزن الاسمنت) في المواد الأولية للخليط الخرساني دون إحداث اي تأثير يُذكر على قوة تحمل الخرسانة للضغط أو على الخصائص الفيزيائية الأخرى مثل الكثافة وامتصاص الماء. أما عند إضافة كمية من الحمأة المجففة بواسطة أشعة الشمس تصل الى ١٠% (من وزن الإسمنت) الى الخليط الخرساني، فإن تحمّل الباطون لقوة الضغط العمودية قد تنخفض بنسبة ٢٠% عند مقارنتها مع باطون من نفس المكونات ولكنه خالٍ من وجود الحمأة - ويرجع ذلك الى وجود تركيز عالٍ من المواد العضوية في الحمأة المجففة والذي يساهم في انفصال مواد الخرسانة عن بعضها البعض مانعاً تشكيل القوة والصلابة للباطون بشكل كامل. أما عند استبدال الرمل المستخدم في المواد الأولية في تصنيع الطوب بكميات صغيرة من الحمأة (إما بكمية ١٠% من رماد الحمأة المحروقة أو بخليط مكون من ٢,٥% من الحمأة المجففة و ٧,٥% من رماد الحمأة)، فلا يوجد تأثير سلبي يُذكر على تشكُّل الصلابة للباطون بعد ٧ أو ٢٨ أو ٩٠ يوم من عمر الخرسانة.

أما بالنسبة للجدوى الإقتصادية، فيمكن تحقيق أكبر توفير في تكاليف انتاج الطوب الإسمنتي عند استبدال استخدام ١٠% من الرمل بكمية مماثلة من رماد الحمأة المحروقة في خليط المواد الأولية دون إحداث أي تأثير سلبي على الخصائص الفيزيائية العامة للباطون الناتج.

KEYWORDS

Sewage sludge-amended bricks; biosolids in concrete; sewage sludge ash; biosolids management

DEDICATION

This work is dedicated to the following:

Birzeit University

Institute of Environmental and Water Studies

Palestinian Water Authority

Austrian Development Cooperation

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No undertaking of this magnitude can be accomplished alone without a lot of good counsel and without the enthusiastic and active support of many remarkable and inspirational people.

This work has been conducted under the leadership and technical guidance of Dr. Eng. Rashed Al-Sa'ed and the financial support of the Palestinian Water Authority through funding from the Austrian Development Cooperation.

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Special appreciation is extended to Dr. Nidal Mahmoud, Director of the Institute of Environmental and Water Studies (IEWS) at Birzeit University, for generously providing me with unfettered and facilitated access to Birzeit University's laboratory facilities and high-tech testing equipment. Dr. Nidal Mahomoud has kept IEWS as the front-runner in the environmental research arena.

I am also thankful for Mr. Ehab Karam, the owner of the largest concrete masonry bricks manufacturing plant (Karam Concrete Production Company) for providing precise information and accurate prices regarding the operational costs of bricks-making processes. He also provided up-to-date wholesale prices of the raw materials that go into the production process.

I would like to thank the technical and management team of the Alquds Center for Civil and Environmental Engineering Studies in Ramallah, for generously opening up the laboratory for me to conduct the majority of the materials testing. Their top-notch lab is an accredited full-service materials laboratory specializing in testing and failure analysis of construction materials, including, but not limited to, steel, concrete, mortars, cement, aggregates, mineral and chemical admixtures. I am thankful for their team for working overtime at the laboratory in order to help prepare concrete mixtures and cast the bricks.

I am grateful to Dr. Shaddad Al-Atili, Director of the Palestinian Water Authority, for his continued efforts in leveraging the PWA's regional position to push the Palestinian agenda in environmental and water research forward. His dedicated staff and engineers have invested timeless efforts in carefully planning, managing, and executing the project that this work is a small part of.

I am also grateful to the Austrian Development Cooperation for funding my work. Their generous financial contribution and support will certainly help realize their vision of promoting environmental research and fostering innovative green technologies.

Special thanks are due to the staff of Al-Bireh municipality for providing me with facilitated access to the Al-Bireh Wastewater Treatment Plant for the purpose of collecting biosolids samples.

I am also thankful to the professional team working at the Al Bireh Wastewater Treatment Plant. Throughout my many visits to the plants, they were helpful, cooperative, and always ready to lend a hand – especially when I had to load the car with and haul away large quantities of dewatered biosolids.

Finally I would like to thank the readers of this work for their vested interest in waste management and cleaner-production research that promotes the preservation of the environment. I am pleased to present this paper to them in hope that they can capitalize on my work or build on it in such a way so as to advance environmental awareness and to help design and implement environmental sustainability strategies at speed and at scale.

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LIST OF ABBREVIATIONS

ACI	American concrete institute
AFR	Alternative fuel and raw material
ARB	Antibiotic-resistant bacteria
ASTM	American Society for Testing and Materials
AWIs	Anthropogenic waste indicators
AWWTP	Al-Bireh wastewater treatment plant
BOD	Biochemical oxygen demand
BPEO	Best practicable environmental option
CA	Coarse aggregate
CBA	Cost benefit analyssi
Cd	Cadmium
CMU	Concrete masonry unit
Cu	Copper
EPA	Environmental Protection Agency
FA	Fine aggregate
FM	Fineness modulus
F/M ratio	Food to microorganism ratio
ISSA	Incinerated sewage sludge ash
MDG	Millennium development goals
MLSS	Mixed liquor suspended solids
Ni	Nickel
OPC	Ordinary Portland cement
Pb	Lead
PCBs	Polychlorinated biphenyls
PCC	Portland cement concrete
PDBEs	Poly-brominated diphenyl ethers

PE	Population equivalent
PFRP	Process to further reduce pathogens
POPs	Persistent organic pollutants
POTWs	Publicly-owned treatment works
PPCPs	Pharmaceuticals and personal care product chemicals
PSRP	Process to significantly reduce pathogens
$P_{X,VSS}$	Net waste activated sludge produced each day (Kg, VSS/d)
Q	Flow (influent wastewater flow) m^3/d
S	Effluent substrate concentration, g/m^3 (mg/L)
S_o	Influent substrate concentration, g/m^3 (mg/L)
Sp	Specific gravity
SRT	Solids retention time
SSA	Sewage sludge ash
SSD	Saturated surface-dry (aggregates)
SSP	Sewage sludge pellets
STP	Sewage treatment plant
TMS	Target mean strength (for concrete)
UN	United Nations
USEPA	United Stated Environmental Protection Agency
VSS	Volatile suspended solids
WCED	World Commission on Environment and Development
WEF	Water Environment Federation
WFD	Waste Framework Directive (European)
WWTP	Wastewater treatment plant
Y_{obs}	Observed yield, g VSS/g substrate removed
Zn	Zinc

UNIT ABBREVIATIONS

Kg	Kilogram
m^2	Square meters
m^3	Cubic meter
ha	Hectares
mg	Milligrams
mm	Millimeters
°C	Degrees Celsius
Mg	Mega gram = 1 tonne ≈ 1.1 ton
Psi	Pounds per square inch
MPa	Mega Pascal = 1,000,000 Pascal
d	day
€	Euro
w/c	water to cement ratio
Yr	Year

CHAPTER 1

INTRODUCTION

1.1 The 'E' in Sustainable Development

To address the growing concerns "about the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development," the World Commission on Environment and Development released *Our Common Future* in 1987 (often called the Brundtland Report) – a report that highlighted sustainable development as the "development that meets needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

In the 24 years since the release of the Brundtland Report, the principle of sustainable development has undergone a lot of evolution and has been much elaborated and refined to entail three E's in its definition: environment, economy, and equity. From the environmental perspective, in order to underpin sustainable development, instead of generating wastes, systems have to be devised to ensure the prudent use of raw materials and natural resources, generating as little waste as possible – i.e. systems for the preservation of natural resources and biodiversity that are smart, comprehensive, and effective. In our increasingly resource-constrained world, the three R's of the waste hierarchy - reduce, re-use, and recycle were a recurring cornerstone in many sustainable development principles. Recently, the European Waste Framework Directive (WFD) expanded the waste hierarchy from a 3-step to a quasi-binding 5-step hierarchy that includes recovery and disposal (European Parliament, 2008) so as to introduce a newer approach that takes into account the whole life-cycle of resources and materials, and to focus on reducing the environmental impacts of waste generation and waste management, thereby strengthening the economic value of waste and encouraging recovery of waste and the beneficial use of the recovered materials.

1.2 Background on the creation and management of biosolids

Wastewater treatment and the management of the solids (in the form of sewage sludge) that it produces are intricate global issues with growing challenges that must be addressed at all levels of stakeholders – wastewater generators, sanitary engineers, treatment facility operators, scientists, regulators, as well as the general public.

The constituents removed in domestic sewage treatment plants are primarily screenings, grit, scum, and sludge – with sludge being by far the largest in volume (Metcalf and Eddy, 1991) and perhaps the most complex to process, store, and render to a pre-disposal form that is suitable and safe for final disposal or re-use.

To put this into perspective, new research shows that as high as 4,000 man-made chemicals (a few are shown in Table 1) that are in common usage may become sequestered in wastewater sludge and can enter the environment when these biosolids are disposed of on land (Deo & Halden, 2010). This is because most wastewater treatment facilities are designed only to remove nutrients, turbidity, and oxygen-depleting human waste, but not the large number of chemicals that are put to residential, commercial, and industrial use. The higher the level of treatment required, the higher are the volumes of wastewater solids being created.

Table 1 | Regulated pollutants in wastewater sludge (Metcalf, Tchobanoglous, & Burton, 1991)

	Type of disposal or re-use				
Pollutant	Land application	Distribution & marketing	Mono-filling	Surface disposal	Incineration
Aldrin	✓	✓			
Arsenic	✓	✓	✓	✓	✓
Benzene			✓	✓	
Benzo(a)pyrene	✓	✓	✓	✓	
Beryllium					✓
Bis(2-			✓	✓	
Cadmium	✓	✓	✓	✓	✓
Chlordane	✓	✓	✓	✓	
Chromium	✓	✓			
Copper	✓	✓	✓	✓	
DDD/DDE/DDT	✓	✓	✓	✓	
Dieldrin	✓	✓			
Dimethyl nitrosamine	✓		✓	✓	
Heptachlor	✓	✓			
Hexachlorobenzene	✓	✓			
Hexacholorobutadiene	✓	✓			
Lead	✓	✓	✓	✓	✓
Lindane	✓	✓	✓	✓	
Mercury	✓	✓	✓	✓	✓
Molybdenum	✓				
Nickel	✓	✓	✓	✓	✓
PCBs	✓	✓	✓	✓	
Selenium	✓	✓			
Toxaphene	✓	✓	✓	✓	
Trichloroethylene	✓		✓	✓	
Total hydrocarbons					✓
Zinc	✓	✓			✓

Table 2 below summarizes the historical evolution of sewage sludge from the year 1500 until 1991 when the word “biosoldis” was coined.

Table 2 | The history and evolution of biosolids

1500 - 1800	**1**	1972 -	**6**
Pre- flush toilets and sewer systems era. Chinese returned human excreta or “night soil” to nearby farmlands.		Federal Water Pollution Control Acts Amendments of 1972 placed restrictions on discharge of pollutants to waterways and encouraged land application of sewage sludge.	
1850 -	**2**	1972 – 1980	**7**
Commercial flush toilets and city sewer systems introduced in Western Europe and North America. Wastewater is discharged without any treatment. Large-scale cropland application of municipal wastewater is practiced.		Source control programs initiated. Industrial pre-treatment programs initiated.	
1875 -	**3**	1987	**8**
“Sewage Farms” are constructed to serve major European cities – farms that are irrigated and fertilized with raw sewage.		Congress directed EPA to: ▪ Identify toxic pollutants that may be present in sludge in concentrations that may affect the public health and the environment. ▪ Promulgate regulations that specify acceptable management practices and numerical concentration limits for these pollutants in sludge.	
1899 -	**4**	1991	**9**
First federal legislation first appeared, aimed at controlling water pollution.		The Name Change Task Force of the Water Environment Federation formally created the term “biosolids.” Possible name suggestions were “humanure,” “bioresidue,” “urban biomass,” “geoslime,” “biolife,” “nutri-cake,” “bioslurp,” “bio gold,” “recyclite,” “organic residuals” “the end product,” “powergro.”	
1900 – 1950	**5**		
Thousands of POTWs constructed (activated sludge process is developed in 1912-1914). Ocean disposal of residual solids is still permitted.			

(Committee on the Use of Treated Municipal Wastewater Effluents and Sludge in the Production of Crops for Human Consumption, 1996)

Worldwide, the produced sludge (i.e. solids) is disposed to landfills, used a source of energy, further processed and used on land as a fertilizer or soil conditioner, or even used as a raw material in the construction industry. When sludge is properly treated and is used on land, it is widely known as "biosolids" in order to distinguish it from other sludge – in the public acceptance domain. Today, many of the chemical pollutants that are sequestered in sewage sludge are regulated (Table 1) in the United States.

1.3 Current levels of sewage sludge production

Higher income countries that have the largest wastewater service coverage and advanced treatment technologies, produce the largest quantities of sewage sludge per capita (see Table 3 below).

Table 3 | Estimated sewage sludge production and populations for selected countries

Country	Annual Sewage Sludge Production (Dry metric tons)	Population	Annual Sludge Production (Kg/capita)
Brazil	372	188,078,000	0.002
China	2,966,000	1,313,974,000	2.257
Turkey	580	70,414,000	0.008
Slovakia	55	5,439,000	0.010
Hungary	120	9,981,000	0.012
Japan	2,000,000	127,464,000	15.69
Canada	550	33,100,000	0.017
Italy	1,000,000	58,134,000	17.20
Norway	86.5	4,611,000	0.019
Czech Republic	200	10,235,000	0.019
USA	6,514,000	298,444,000	21.83
Portugal	236.7	10,606,000	0.022
Germany	2,000,000	82,422,000	24.27
UK	1,500,000	60,609,000	24.75
Slovania	57	2,010,000	0.028
Finland	150	5,231,000	0.029
Netherlands	1,500,000	16,491,000	90.96

((UN-Habitat), United Nations Human Settlements Programme, 2008)

Conversely, middle-income countries which have under-developed and less comprehensive septage treatment infrastructure produce far less sewage sludge per capita on the national level.

In Palestine for example, only 52.1% of households are connected to functional wastewater networks. Moreover, cesspits are still in use by more than 45.5% of Palestinian (Palestinian Central Bureau of Statistics, 2009). This means that, as of the year 2009, only half of the Palestinian population were actively contributing to sludge production.

Table 4 below shows the estimated future projected biosolids production rates for developing countries. Jordan, for example, will need about 3% of its agricultural land to accept biolsolids application at a rate of 5,000 Kg/ha in order to dispose of the biosolids.

Table 4 | Predicted future sewage sludge production if developing countries attain levels of wastewater service coverage of developed countries

Country	Estimated future sludge production (Metric tons/yr)	% of agricultural area required to apply country's future sludge at 5 Mg/ha
Developing Countries		
Brazil	4,069,339	0.31%
Bulgaria	159,793	0.61%
Burkina Faso	300,811	0.55%
Cameroon	375,191	0.82%
China	28,429,686	1.02%
Colombia	943,197	0.44%
Cote D'lvoire	381,988	0.38%
Ethiopia	1,617,928	0.95%
Hungary	215,96	0.74%
Iran	1,486,172	0.62%
Jordan	127,801	2.53%
Mali	253,51	0.13%
Mexico	2,324,823	0.43%
Mozambique	425,945	0.18%
Namibia	44,228	0.02%
Nigeria	2,852,972	0.77%
Russia	3,091,705	0.29%
Senegal	259,358	0.63%
South Africa	956,062	0.19%
Turkey	1,523,506	0.74%
Palestine (WB)*	7,028	N/A
Developed Countries		
Germany	1,783,323	2.1%
Netherlands	356,816	3.7%
Japan	2,757,856	11.8%
United Sates	6,457,264	0.3%

*Calculated value based on equation 1 below and on a present population of 4,043,218; population growth rate of 2.25%; SRT of 10 days; temperature of 20 °C; average daily wastewater inflow flow of 5000 m^3/d; average influent and effluent substrate concentrations of 500 mg/L and 10 mg/L respectively. ((UN-Habitat), United Nations Human Settlements Programme, 2008)

The future bio-solids production rate in Palestine in Table 4 was calculated (Appendix 2) based on an estimate of observed solids yield data from similar facilities (Figure 1) combined with data collected at a major wastewater treatment plant as shown in equation below (Asano, 2007):

$$P_{X,VSS} = Y_{obs}(Q)(S_o - S)(1\ Kg/10^3\ g) \qquad \text{(Eq. 1)}$$

where

$P_{X,VSS}$ = net waste activated sludge produced per day, Kg VSS/d
Y_{obs} = observed yield, g VSS/g substrate removed
Q = influent flow, m^3/d
S_o = influent substrate concentration, g/m^3 (mg/L)

S = effluent substrate concentration, g/m^3 (mg/L)

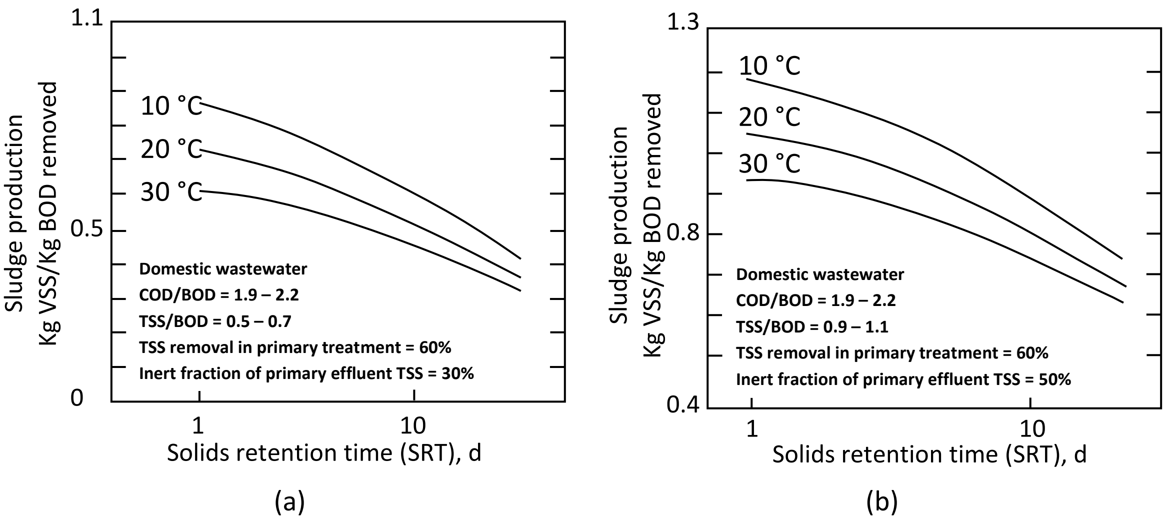


Figure 1 | Net solids production versus solids retention time (SRT) and temperature: (a) with primary treatment and (b) without primary treatment (Asano, 2007)

1.4 Public acceptance barriers to biosolids recycling

In many countries the general public has not actively participated in the growing dispute on sewage sludge recycling techniques. In general, however, communities that are served by WWTPs are inclined to maintain existing routes for sewage sludge disposal/reuse that are both economically viable and safe in terms of health. In the media and public, there are growing and widespread concerns about the traces of chemicals and heavy metals, about disease transmission and antibiotic resistance.

At the legislative national level, of all the options for the disposal and recycling of biosolids, ministries and environmental agencies are in favor of adopting and further developing the use of processed sludge in agriculture, as it is considered to be the best economic and environmental option to deal with the increasing quantities of sludge produced (European Commission DG Environment, October 2001).

Often the best environmental and most energy-efficient solution for septage sludge management is not supported by the public – largely because people prefer that anything associated with human excreta be managed in remote areas (the *out of sight and out of mind* thinking approach). The major public acceptance barrier to sewage sludge reuse is often triggered by the widely held perception of sewage sludge as malodorous, disease causing or otherwise repulsive. Pathogenic microbes in biosolids are one of the key factors influencing public acceptance of biosolids re-use. Possible viable pathogens include bacteria, viruses, and parasites. Pathogen concentrations in sewage are directly related to the occurrence of these pathogens in the community contributing to the sewage flow. However, regardless of initial levels, pathogens become relatively concentrated in biosolids.

Table 5 summarizes a list of historical and potential future disposal outlets for biosolids management. As the table shows, most of the past, current, and future beneficial uses of biosolids are in the land reclamation, horticulture, and landscaping domains

Table 5 | Historical and potential future beneficial uses of biosolids

Land Reclamation

- Land reclamation of mine-lands (metal mines, aggregate/sand/gravel mines, coal mines
- Landfill closures (as a component of topsoil in closure activities)
- Lime stabilized biosolids to mitigate acid mine drainage
- Remediation/bioremediation (e.g. with compost of Fe-rich biosolids) for urban/suburban contaminated sites.
- General topsoil manufacturing for other uses (in combination with other residuals such as paper mill residuals).
- Restoration and development of water features (e.g. wetland establishment/enhancement; shoreline restoration).

Horticulture and Landscaping

- Compost feedstock
- Potting mixes
- Fertilizers (e.g. heat-dried pellet fertilizer)
- Sod production
- Lawns, parks, sports fields
- Green roofs
- Erosion control (e.g. compost berms)
- Treatment of storm-water flow (compost filters, filter socks)
- Highway re-vegetation
- Using incineration ash for phosphorous and liming value in soil mixes

Forestry

- Forest fertilization (i.e. in existing stands and for reforestation
- Applications following forest fires
- Intensive silviculture for fiber crops (e.g. hybrid poplar, trench applications, etc)

Industrial Processes

- Use in cement kilns
- Making bricks and other building materials
- Making glass aggregate used in pavements
- Daily or final landfill cover

Resource Recovery

- Biosolids as source of minerals and metals (e.g. struvite production)
- Substrate for high value products (e.g. proteins)

Energy Recovery

- Bio-energy from digestion (in digesters or deep bores)
- Incineration (thermal oxidation or thermal conversion) with heat recovery and/or electricity generation
- Gasification, pyrolysis, and other developing high-tech energy production options

(Beecher, Hébert, Ham, & Teshima, October, 2007)

1.5 Factors influencing current and future biosolids management practices

The disposal and/or re-use of sludge require very careful management which can get complicated due to the presence of a wide range of factors influencing the decision-making process. Figure 2 below summarizes the numerous factors (such as regulations, public perceptions, and economics) that can play a critical role in the management of biosolids.

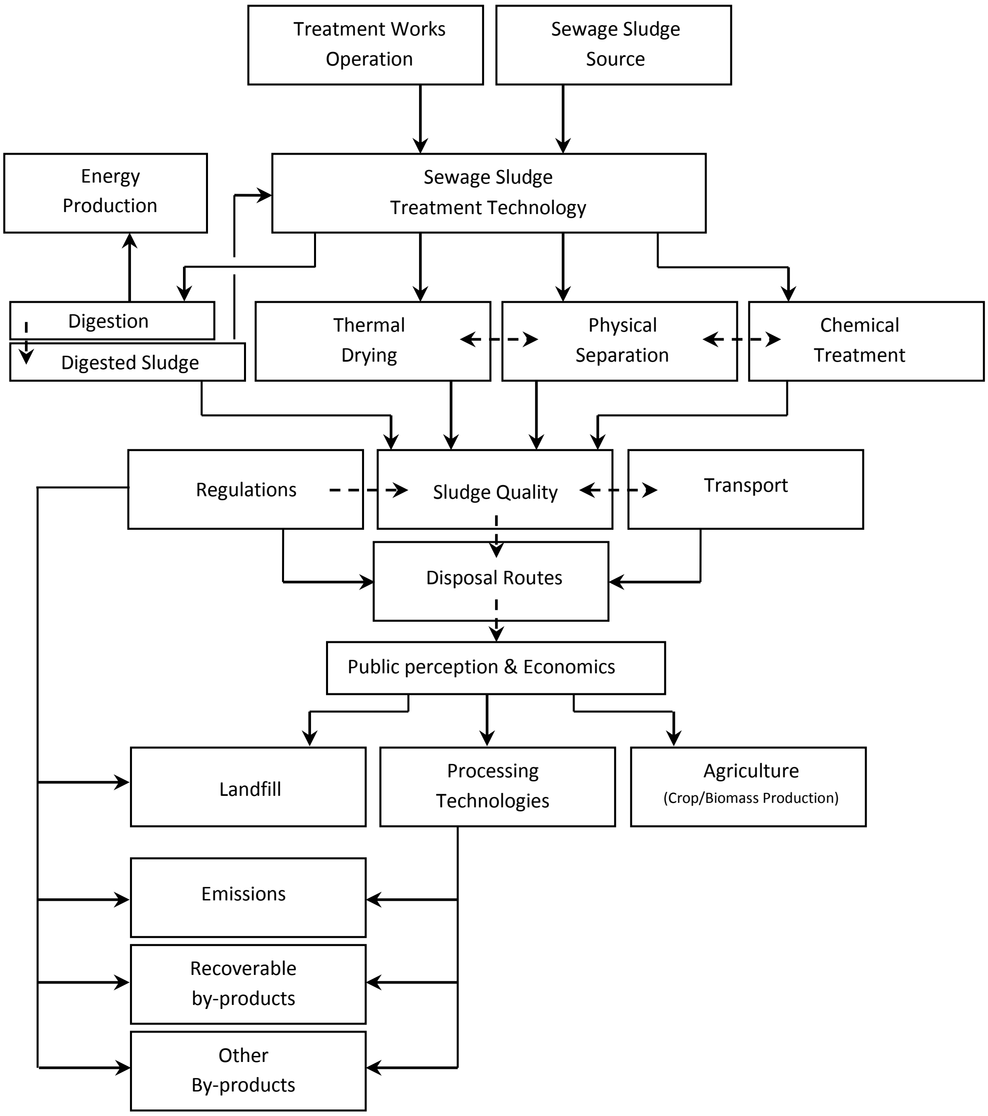


Figure 2 | Factors affecting disposal/treatment routes for sewage sludge (European Commission DG Environment, October 2001)

1.6 Research objective

The main objective of this work was to investigate the technical and market potential of producing precast concrete bricks that are amended with stabilized sewage sludge as well as with incinerated sewage sludge ashes. The feasibility of incorporating biosolids and biosolids ashes into the manufacturing process of concrete bricks without affecting the physical properties of the cured concrete could possibly offer an attractive and cheap sludge disposal option. The research was built on available literature and current research results, and also made use of new data that was gathered directly on a lab-scale level.

CHAPTER 2

LITERATURE REVIEW

2.1 Background and introduction

The effective management and safe disposal of municipal wastewater bio-solids is a complex and environmentally sensitive issue facing wastewater treatment engineers, environmental practitioners, regulatory authorities, as well as the general public. Scientific evidence has shown that municipal sewage sludge may contain a wide variety of dangerous pathogens, toxic heavy metals, endocrine disruptor chemicals, carcinogens, pharmaceutical drugs, and a host of other recalcitrant micro-pollutants (Haynes et al, 2009; Sidhu and Toze, 2009), originating from residential sewers, hospital drains, and storm water runoffs. Uncontrolled and irresponsible disposal of wastewater bio-solids can disrupt fragile ecosystem functions, destroy biodiversity-rich habitats, and pollute pristine natural resources – thereby causing profound detrimental impacts on plants, farm animals, and humans (Spinosa & Veslind, 2001).

To avoid potential adverse implications, management agencies at multiple regulatory levels are implementing established sewage sludge re-use standards based on chemical and biological components that are of prime concern. These standards are dynamic and are regularly updated as new contaminants are discovered or as research studies provide new scientific evidence about potential risks that were previously thought of as being safe.

Traditionally, sewage sludge is processed and stabilized and then disposed of through various channels including but not limited to land-application, land-filling, and incineration (Malliou et al, 2007). Today, such practices are largely regulated and emphasis is shifting towards the sustainable management of bio-solids - giving rise to the introduction of new and innovative technologies that promote sludge re-use and resource recovery. In other words, effective sludge management systems are getting simpler, not more complex, and are proceeding in the direction of increasing the degree of idealness as shown in equation below (Rantanem & Domb, 2008):

$$Ideality = \frac{\sum Benefits}{\sum Costs + \sum Harms} \quad \text{(Eq. 2)}$$

Where the maximum value of ideality is reached when the benefits are high and the denominator is almost zero (i.e. the most ideal bio-solids management system is the one that achieves maximum benefits with little or no costs and with little or no harm).

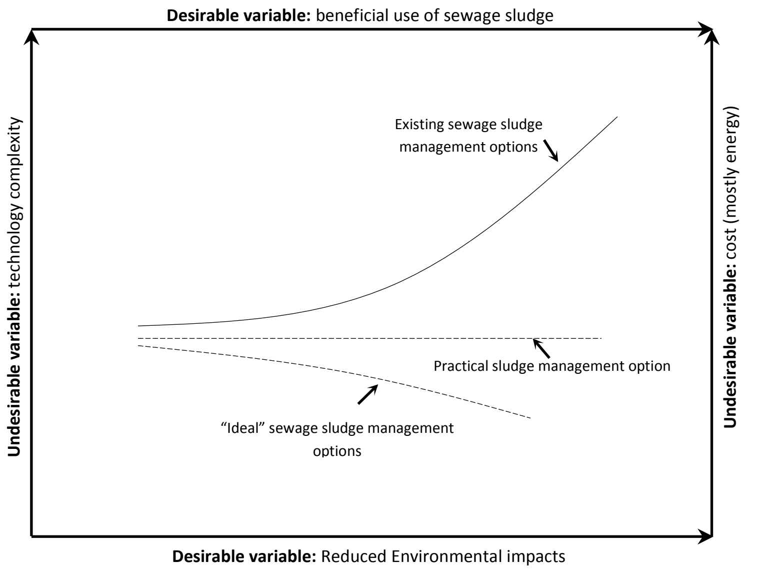


Figure 3 | Classification of existing, practical, and ideal sewage sludge management systems in terms of desired and undesired variables (self-drawn)

2.2 Incineration as a management option

Incineration is a viable alternative to both land spreading and disposal to landfill for sewage sludge. Following the ban on disposal to the North Sea in 1998, sewage sludge incineration was considered as the best practicable environmental option (BPEO) for the management of the domestic sewage solids produced in East London (Cheesman & Virdi, 2005). Sewage sludge incineration is considered a high-technology and high-cost bio-solids minimization option (Hall, 1999) - as it required a large capital investment in infrastructure and requires fuel. Whilst incineration reduces the sewage sludge's volume by up to 70%, the resultant sewage sludge ash (SSA) is considered to be a toxic waste and will incur further expenses for its proper management and safe disposal. In the West Bank, wastewater sewage sludges are transported off-site and are discarded into existing general dump sites for domestic waste, where they are liable to be incinerated alongside other solid waste materials. The resulting emissions add to the alchemy of harmful gases contributing to climate change and health hazards to residents living nearby. As a matter of fact, a study conducted by the Agency for Toxic Substances and Disease Registry concluded that men residing close to a landfill site had elevated risks for prostate, stomach, liver, and lungs cancer, while women had elevated risks of cervix uteri cancer (Goldberg, Seimiatyck, DeWar, Desy, & Riberdy, 1999).

On the other hand, incineration of sewage sludge has become very common in the Netherlands and in Switzerland and is gaining increase acceptance elsewhere in the European Union, mostly driven by the public dislike of land filling and by the growing concerns about potential hazards caused by land application. The megalopolis of Hong Kong, which has very little agricultural land, is turning away from landfills towards incineration.

Table 6 | Percentage of wastewater sludge incinerated by country

Country	Percentage of wastewater sludge incinerated
Japan	70%
Netherlands	58%
Germany	34%
Canada	33%
USA	15%

2.3 Land application as a management option

So far, land application has been the preferred and dominant paradigm for the recycling of nutrient-rich and organic-rich bio-solids – as it enhances soil properties and stimulates vegetative growth. Bio-solids contain the same soil-enriching, plant-boosting elements found in expensive chemical fertilizers – namely nitrogen, phosphorous, and potassium. Table 7 and Figure 4 below show that wastewater bio-solids can contain up to 65% and 23% of the nitrogen and phosphorous that are present in typical commercial fertilizers - thereby reducing the need for chemical fertilizers and thus offering reasonable cost advantages to farmers who choose to use this valuable resource.

Table 7 | Nutrient levels in commercial fertilizers compared to levels in bio-solids

	Nutrients (%)		
	Nitrogen	Phosphorous	Potassium
Fertilizers for typical agricultural use	5	10	10
Stabilized sewage sludge (bio-solids)	3.3	2.3	0.3

(Metcalf, Tchobanoglous, & Burton, 1991)

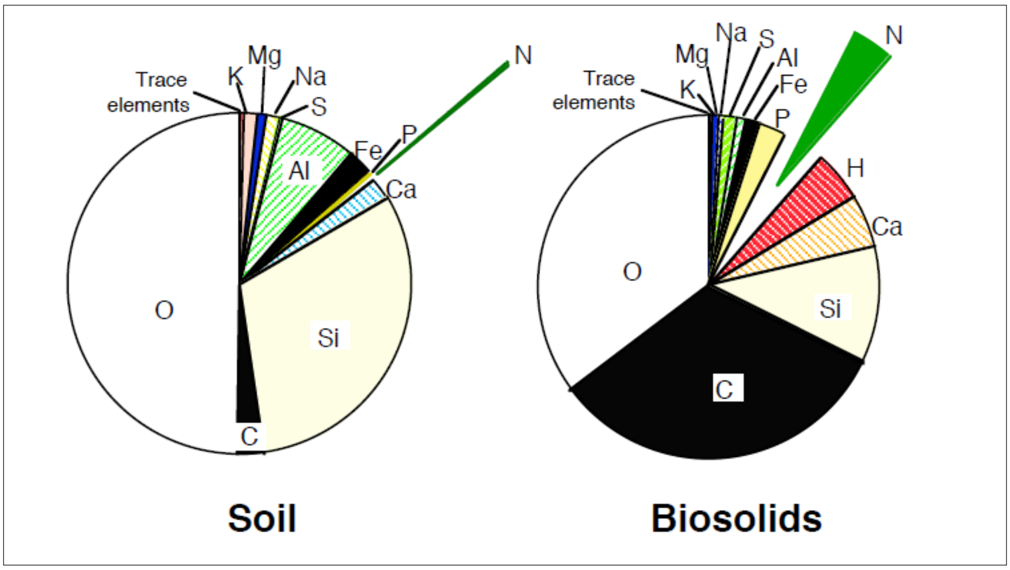


Figure 4 | Comparing the constituents of biosloids to those of soil (C. Henry, UWB)

However, despite the large volume of scientific research done on bio-solids, and in spite of the considerable improvements in quality and developments in wastewater treatment technologies, sludge use acceptance in agriculture continues to attract controversy and skepticism, with environmentalists pushing for regulated land spreading of sludge while the end consumer opposing its use – as sewage sludge is widely perceived by the general public as refuse toxic waste (because of its fecal connotation and origin) and not a product of value.

In fact, sewage sludge comes with wide array of potentially-toxic anthropogenic waste indicators (AWIs) including pharmaceuticals, pesticides, anti-bacterials used in soaps, industrial synthetic chemicals, fragrances used in perfumes and detergents, heavy metals, and other chemicals that wastewater treatment plants aren't capable of removing. Though the US EPA has promoted and endorsed the use of sewage sludge as fertilizer for many years, a fairly recent study revealed that earthworms living in sludge-treated soils were absorbing the pharmaceuticals and personal care product ingredients (PPCPs) that WWTPs left behind concentrated in the sludge. In fact, 25 of the 28 AWIs detected in the biosolids applied to a soybean field were also found in the earthworms from the same field (Kinney, et al., 2008). Even though such a study highlights the earthworms' remarkable ability to detoxify soils, yet, the results has led many scientists to suspect that chemicals can build up in the crops growing in the treated soil and eventually find their way up through the food chain.

Table 8 summarizes some of the EPA regulated trace elements that can be present in biosolids when used in land application.

Table 8 | Trace elements ceiling values (United States Federal Register, 1993)

Nutrients	Typical Biosolids (mg/kg dry)		U.S. Regulations Land Application(1) (mg/kg dry)	U.S. Regulations Home Garden(2) (mg/kg dry)	U.S. Regulations Crop Production(3) (Kg/ha)
NH4-Nitrogen	0.57 ± 0.30		---	---	---
Organic N	4.13 ± 1.03		---	---	---
Total P	2.27 ± 0.89		---	---	---
Total Potassium	0.31 ± 0.27		---	---	---
pH	7.0 ± 0.5		---	---	---
Pollutants	**Range**	**Median**			
Arsenic	1.1 - 230	10	75	41	41
Barium	N/A	N/A			
Boron	N/A	N/A			
Cadmium	1 - 3,410	10	85	39	39
Chromium	10 – 99,000	500			
Cobalt	11.3 – 2,490	30			
Copper	84 – 17,000	800	4,300	1,500	1,500
Iron	1,000 – 54,000	17,000			
Lead	13 – 26,000	500	840	300	300
Manganese	32 – 9,870	260			
Mercury	0.6 - 56	6	57	17	17
Molybdenum	0.1 - 214	4	75		
Nickel	2 – 5,300	80	420	420	420
Selenium	1.7 – 17.2	5	100	100	100
Silver	2.6 - 329	14			
Zinc	101 – 49,000	1,700	7,500	2,800	2,800

(1) Recommended ceiling limits acceptable for land application
(2) Maximum monthly average trace element concentrations (Lawns/home gardens in residential locations)
(3) Maximum cumulative application of trace elements that can be applied to soils for crop production

Furthermore, data from numerous scientific studies showed that bio-solids-treated soils contained higher antibiotic-resistant bacteria (ARB) than the un-amended soils (Auerbach et al., 2007; Brooks et al., 2007; Munir et al., 2010) – thereby supporting the public's concern of the potential health hazards associated with the long-term utilization of bio-solids as fertilizers.

2.4 Land filling as a management option

Modern, state-of-the-art landfills are carefully regulated facilities, managed to reduce air pollution, control leachate and minimize odors. In cases where the beneficial use of bio-solids for agronomic purposes is neither applied nor practiced, sanitary landfills may become the designated final burial sites for the stabilized bio-solids. In almost all countries, sewage sludge must be dewatered to at least 15-20% solids prior to land filling to avoid the excessive generation of leachate. Whilst dewatering is costly, it is often the only requirement for burying sewage sludge in a land fill – making it an easy management option for many countries – especially in countries where there is sizable public concerns about biosolids applications to soils.

Today, there is a worldwide understanding of the problems associated with biosolids' disposal in landfills. The European Union, for example, has directed the phasing-out the land-filling of organic wastes mostly because of the concerns about the releases of methane – a potent greenhouse gas. Japan is recognizing wastewater sludge as too valuable a resource to reject and is now focused on avoiding land filling of organic wastes. Australia reports that "landfilling is not considered a beneficial use of bio-solids and is not, or soon will not, be an acceptable option in any state or territory." Austria does not allow sludge land filling if it contains more than 5% total organic carbon by dry weight or if it contains more than 6000 KJ of energy per kilogram dry weight.

2.5 Cost comparison of disposal and recycling routes for sewage sludge

Sludge amounts to about 2% by volume of processed domestic sewage, but handling it accounts for up to 50% of the total operating costs of a typical wastewater treatment plant (Lehr & Keeley, 2005). Regardless of the sewage sludge disposal and/or recycling route under investigation, the total costs involved are mainly comprised of:

I. Investment costs (including land, equipment, installation, and civil works)

II. Operating costs (including labor, energy, and transportation) required for sludge conditioning and treatment before disposal/recycling.

Figure 5 shows the average total costs of sludge disposal and recycling in Europe with land spreading routes as the best ranking while land filling and incineration are the worst ranking disposal routes in terms of overall cost (European Commission DG Environment, 2002).

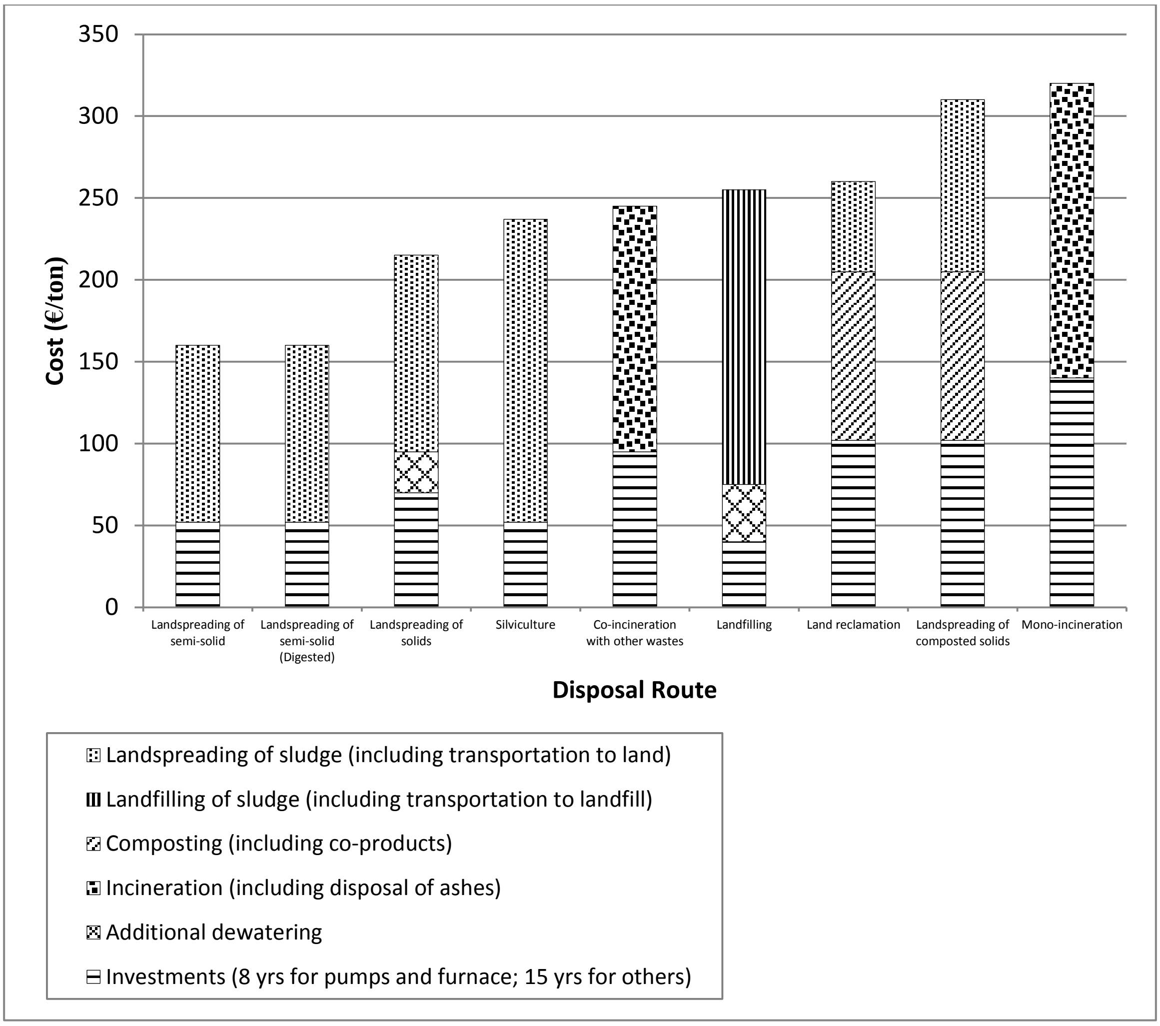


Figure 5 | Average total cost of various disposal/recycling routes of sewage sludge in Europe (European Commission DG Environment, 2002)

Figure 6 shows a cost-benefit analysis (CBA) of a wide range of solids disposal outlets. The land-spreading of composted biosolids is identified as the most re-use option for wastewater sludge with benefits reaching up to € 70/ton. The benefits in this route are reaped in the form of fertilizer savings.

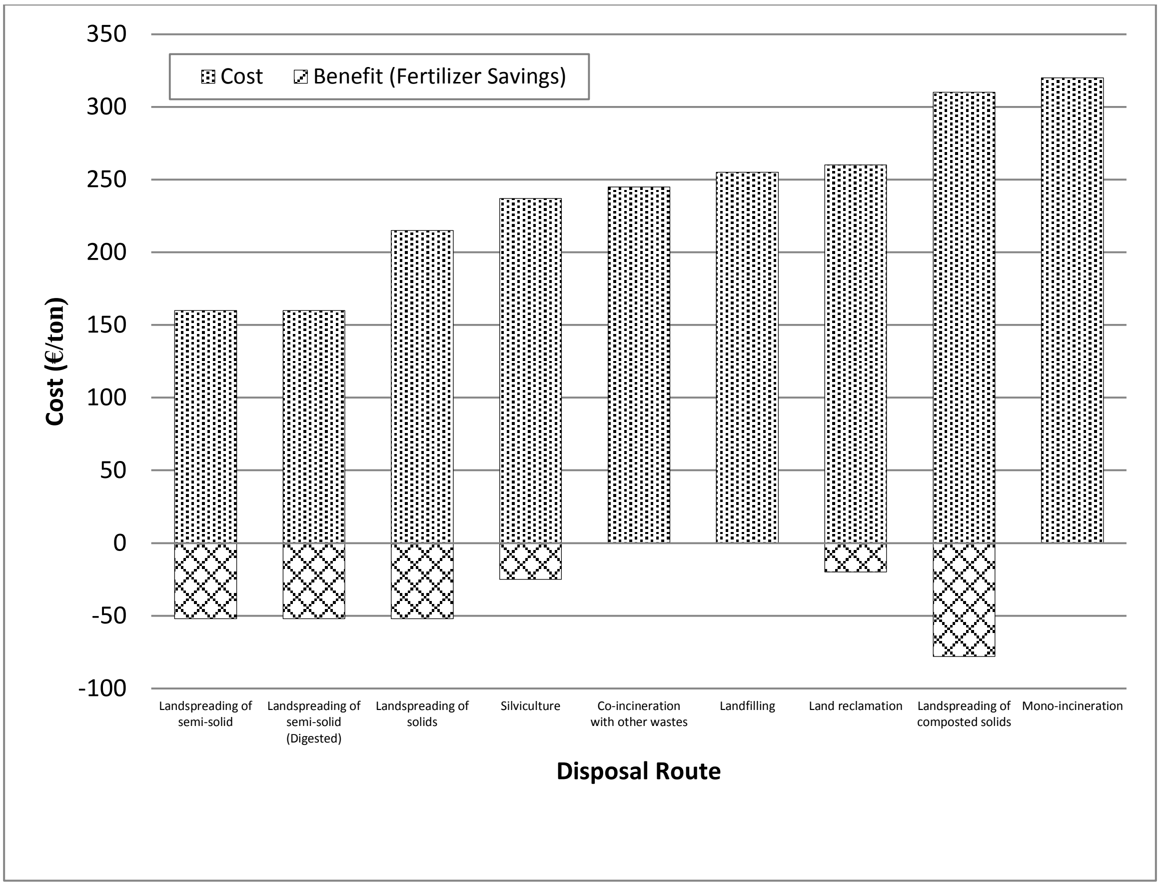


Figure 6 | Average total costs and benefits (shown as negative values) of various disposal/recycling routes of sewage sludge in Europe (European Commission DG Environment, 2002)

2.6 Sewage sludge as a construction material

As increasingly stringent environmental-control mandates are introduced and enforced, the traditional disposal routes of land application, land-filling, and incineration of processed bio-solids will come under pressure and may no longer be viable and cost-effective disposal outlets for sanitary engineers to capitalize on (Wang et al, 2008). Furthermore, the extraction of natural aggregates (i.e. sand, rock, and gravel) for use in building materials is associated with detrimental environmental impacts – with some countries moving to impose taxation laws on such excavation practices. As a result, the viability of using alternative aggregates - such as biosolids - as building materials is expected to increase.

2.6.1 Background

The rapidly growing world population - expected to increase from 6.5 billion today to 9 billion by 2050 - along with the torrid economic proliferation in much of the developing world, will exert stress on existing wastewater treatment facilities requiring them to be expanded and upgraded. As urban planning progresses (every week, from now until 2050, over one million people will added to cities) and new investments are poured into building new excreta and wastewater collection and treatment systems, the global sewage sludge production rates will be on the rise and massive stockpiles of the generated bio-solids will require more cost-effective, efficient, and environmentally friendly management practices.

In order to meet the challenges of controlling the quantity and characteristics of bio-solids in such a way that adverse environmental implications are minimized and beneficial uses are optimized, innovative technologies are being developed, investigated, and applied that make the end use of bio-solids (particularly those of industrial origin) - as a non-conventional building material - an economically-viable alternative.

Concrete is by far the most widely used construction material in the world and it plays a vital role in all infrastructure construction and earthworks. Concrete's versatility allows it to bind with many types of materials and engineers are focusing on finding new, cheaper, and environmentally-friendly aggregates that can increase the durability of concrete while decreasing the production cost at the same time.

Civil engineers have succeeded in re-using brick rubble, crushed concrete, and other construction/demolition/excavation waste materials as concrete admixtures to construct new roads along with their embankments. Sanitary and environmental researchers have taken the work of their civil engineering counterparts a little further by exploring the feasibility of incorporating solids and organic wastes into concrete works. In this domain, their recent research work revolved around exploring the use of bio-solids or bio-solids ashes as a core ingredient or as an admixture in the manufacturing of precast bricks or concrete blocks intended for use in the non-load bearing building and construction industry. Furthermore, stabilized sewage sludge has also been investigated as a potential alternative fuel resource (AFR) that can be used in kilns for the manufacturing process of cement and other cementitious materials.

The diagram in Figure 7 shows an overview of the lifecycle of re-using sewage sludge in the cement industry domain. The mixing of biosolids with cement is intended to minimize the use of virgin building materials and increase the use of recycled materials as well – a strategy that can help in the development of an “ideal” management option to the sewage sludge disposal dilemma (see Figure 3).

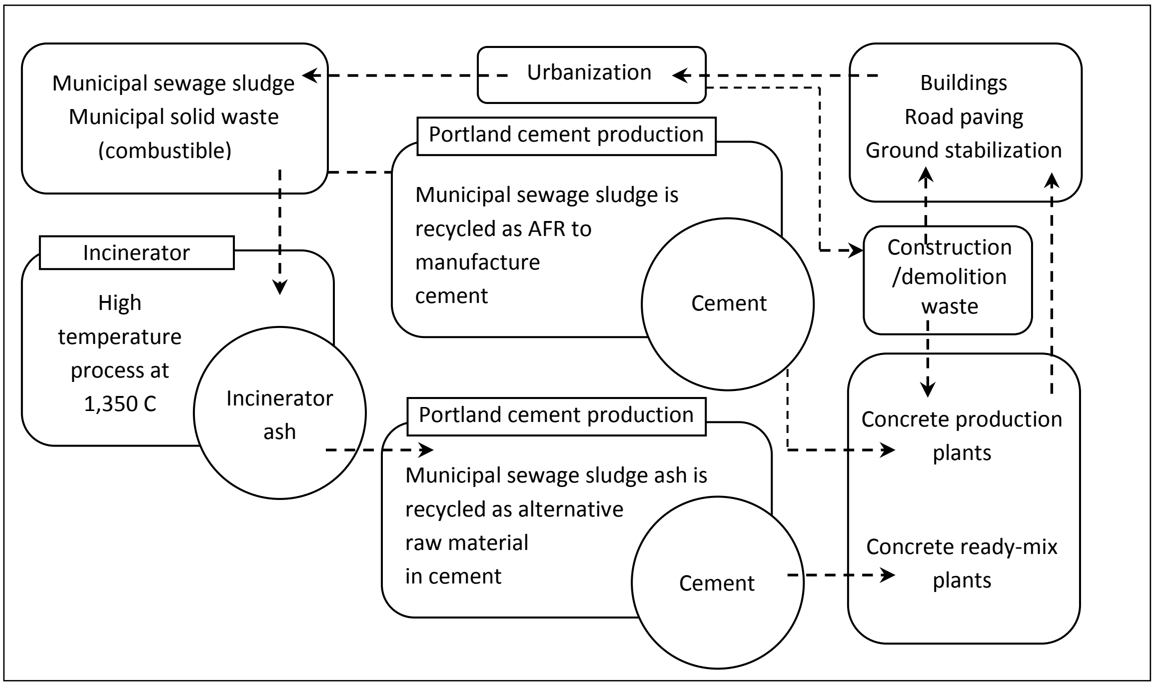


Figure 7 | Lifecycle of municipal sewage sludge when re-used and re-cycled to make cement

In light of the biosolids production-disposal lifecycle, viewing sludge as a marketable product implies that sludge production should be optimized at the source, rather than minimized.

2.6.2 Use of biosolids and biosolids ash in clay bricks

Numerous studies have shown that sewage sludge may be used as a partial substitute for clay in clay-brick manufacturing. A mixture of clay and sewage sludge ash can be molded and fired at high temperatures to produce high-grade clay bricks (Alleman and Berman, 1984; Alleman et al., 1990; Liew et al., 2004; Slim and Wakefield, 1991; Tay, 1987; Trauner, 1993; Wiebusch and Seyfried, 1997). The optimal conditions for manufacturing good quality clay bricks is by the addition of a maximum of 10% sludge (containing 24% moisture) to the clay mixture that is then molded and fired at 880-960 °C (Weng, Lin, & Chiang, 2003).

2.6.3 Wastewater sludge as a cementitious and blended cement materials

Other researchers studied the use of sludge ash as a lightweight aggregate that can enhance the thermal insulation and fire protection properties of concrete. Documented results indicated that it is possible to replace up to 30% by weight of fine aggregate by sludge ash in a concrete mix to produce blocks with adequate mechanical resistance to be used as a building material (Kato and Takesue, 1984; Khanbilvardi and Afshari, 1995; Yip and Tay, 1990). Okuno and Takahashi demonstrated that through high-pressure thermal solidification of 100% sewage sludge, the manufacturing of flooring bricks - mainly used for walkways and sidewalks paving - can be a technically and economically feasible production process (Okuno and Takahashi, 1997). However, the production process is complex and involves high-pressure compaction and precisely-controlled firing temperatures.

Monzo et al., (2004) used thermally-dried sewage sludge pellets (SSP) to replace 6.1% (dry weight) of the sand in the concrete mix to be used for paving purposes. The addition of SSP yielded a slightly lower flexural and compressive strengths compared to the control, but the addition of a hardening accelerator to the mix compensated for the decrease in strength and produced paving concrete with similar strength characteristics as the control.

In a similar study, Yague et al., (2002) found that the addition of 2% of dried sewage sludge (to cement weight) had no adverse effect on the compressive strength or on the durability of concrete bricks. In fact, some SSP-amended concrete bricks exhibited higher compressive strength than the reference bricks after 1 year. In a follow up study in 2005, Yague et al. used a 10% sludge to cement (by weight) concrete mix. Even though its mechanical strength was largely reduced, the durability of the produced concrete was comparable to results obtained for the reference concrete not containing sludge.

2.6.4 Biosolids use in load-bearing structures

From an economic standpoint, a recent study conducted in Thailand showed that incorporating 20% wastewater sludge in a concrete mixture – particularily as a partial replacement of the fine aggregate can produce load-bearing hollow cement blocks at a 20% reduced manufacturing cost (Kaosol, 2010). The author did not however address how his pilot-scale work can be scaled-up and transferred to a cost-competitive production lines that can be put to use on a large-scale level.

2.6.5 Industrial sewage sludge use in concrete works

While farmland application of stabilized domestic sewage sludge (bio-solids) is commonly accepted and widely practiced in many countries, the safe disposal of *industrial* sewage sludge poses a serious dilemma to regulating authorities because of concerns of contamination of the food chain by sludge-laden toxic substances, organic pollutants, and heavy metals. The effective utilization of such bio-solids as raw materials in cement has been shown to immobilize the heavy metals in the final molded brick – hence becoming an integral part of the finished product (Lim et al., 2006; Weng et al., 2002) and thus eliminating their bioavailability.

In Egypt, a recent study provided compelling evidence that ornamental bricks with acceptable compressive strength can be produced and safely used, with up to 4% industrial sewage sludge that are heavily contaminated with the highly toxic metalloid: arsenic. The experimental arsenic-containing bricks passed strict leachability tests and are therefore not regarded as hazardous (Mahzuz et al., 2009). Moreover, Montgomery et al (1988), demonstrated that the cement solidification of heavy metals-rich sewage sludge causes Zincn, Lead, and Cadmium to be bound up in the cement matrix as insoluble hydroxides (Montgomery et al, 1988) – thereby inhibiting the metals' mobility through physical encapsulation.

2.6.6 Potential technical limitations

In spite of the successes demonstrated in the novel utilization of biosolids as a new material in concrete production, there remain many key technical challenges to be tackled and overcome - particularly those associated with the durability and stability of the finished and cured product.

Bricks cracking and shrinkage, during and after the manufacturing and curing processes, are two main problems encountered if in excess of 30% by weight dry sludge is used as core ingredient in the raw material mixture (Liew, 2004).

Brick whitening problems due to the re-crystallization of leached calcium carbonate posed an aesthetic concern when the bricks were used for paved pedestrian walkways (Okuno and Takahashi, 1997). Furthermore, compressive (crushing) strength is slightly reduced and water absorption and porosity are increased as sludge dosing rates are increased in the manufacturing of bricks (Pinarli and Emre, 1994).

Another challenge is the increased porosity of the cured blocks. Many structural fills require high compaction rate of concrete. The organic matter present in biosolids-amended concrete does not allow the concrete to compact properly to the required density.

2.6.7 Local barriers

The potential use of stabilized sewage sludge as an additive in construction materials such as asphalt concrete, bricks, and cement blocks has been widely demonstrated on a lab-scale level and appears to provide a promising large-scale application alternative to bio-solids landfill disposal if market conditions are appropriate and if social barriers are properly addressed and overcome. In Palestine however, the shift to greener production and to eco-innovations is still in its infancy stages, and thus no attempts have been made so far to fully explore the potential use of bio-solids produced from wastewater treatment plants as a new material in the construction sector. The primary barrier is that the potential benefits are not adequately taken into account by urban planners and sanitary engineers. In addition, the widespread adoption of bio-solids recycling technologies in Palestine is hindered by undeveloped markets, high transportation costs, health and cultural issues, as well as by absence of regulations.

Even though the shift to producing this kind of “green” concrete can help solve the bio-solids management puzzle – nevertheless, it may not be the ideal solution option. This is because scaling-up the technology and creating a mass market large enough to give birth to a completely new and sustainable bio-solids management pathway can be a difficult task. Furthermore, public acceptance and understanding of the science behind new environmental innovations can be a critical factor in large-scale technology adoption and commercialization and successful market penetration. Therefore, it will be imperative for future research to evaluate the general public perceptions and attitudes related to incorporating bio-solids into building materials as well as to gauge their willingness to purchase and use such products.

It is worthwhile to mention here that during the period that this study was being carried out, owners of local pre-cast concrete production plants refused my repeated requests to try to produce sample bricks blended with biosolids or sludge ashes at their facilities without stating the reasons behind their refusal.

2.6.8 Increased energy costs

On close examination of the previous and current scientific research by which sewage sludge was used in the construction industry, almost all of the testing and production processes involved the use of energy to transform the sewage sludge into sewage sludge ash before incorporating it into concrete works. In cases where sewage sludge with high organic content is incorporated in concrete works, thermal drying was used predominately to dry the sludge to form sewage sludge pellets. Again, this results in added cost in terms of energy expenses. Other processes involved the use of high firing temperatures and pressures (i.e. thermal solidification - which translates into high energy costs) to mold and form bricks made with 100% raw sewage sludge. Most of these technologies will never be able to reach the market – this is because, in order to increase the ideality of an effective biosolids management system one has to decrease its energy consumption and not the other way around.

CHAPTER 3

RESEARCH DESIGN AND APPLIED METHODOLOGIES

3.1 Introduction

The potential reuse of wastewater bio-solids and incinerated sewage sludge ashes as additives into construction materials may alleviate sludge disposal problems and offer economic, ecological, and energy saving advantages at the same time.

3.2 Experimental approach

In this study, the incorporation of sewage sludge and sewage sludge ashes into concrete blocks was systematically investigated. The proportion of sludge and ashes in the concrete bricks was varied in order to determine the resultant positive or negative effect on the efficiency of the concrete manufacturing process and on the produced product. In each of the experimental trials, the quantity of cement and water used in the concrete mixture were kept constant.

The approach was to experiment with various sludge dosing ratios (making use of both solar-dried biosolids and sewage sludge ashes) and then to evaluate and analyze the corresponding physical properties of the concrete mix paste and of the produced concrete bricks – mainly those properties affecting the structural integrity of the cement mix and of the cured concrete. Physical property results are then compared and contrasted against those for pre-cast concrete bricks that are free from any biosolids or sewage sludge ashes (i.e. control samples).

The words “concrete bricks” and “concrete blocks” are used interchangeably throughout this study and they refer to hollow or non-hollow concrete units made from sand, crushed stone, water, and cement and that can be used in general-purpose outdoor building of non-load-bearing walls and structures. The bricks are moist-cured but are not subjected to any heat or firing during or after the curing process. Figure 1 shows a typical semi-automatic facility that produces these kinds of bricks located in the Ramallah area.

Figure 8 | Typical concrete bricks-manufacturing facility located in the city of Ramallah

Furthermore, the economic feasibility of producing and marketing sewage-amended concrete blocks was also investigated. This was accomplished by carrying out a production cost analysis of the most widely produced and used concrete masonry unit in the West Bank area. Brick production costs were based on already established brick-making factories as they are usually looking for innovative ways to cut production costs without compromising on quality.

Assuming that the cost analysis will involve factories in operation, the variables to be determined were based on operational costs and raw materials costs only. It is assumed there will be no major modification to the brick production processes. The only additional capital and investment cost is assumed to be incurred by the WWTP to dry, grind, and store the sludge to make it in a form that is usable by concrete manufacturing plants.

The production cost of a unit brick is estimated using the conventional raw materials and is then compared to the production cost of the same unit brick but using sewage sludge i) as an additive to the raw materials; ii) and as a partial replacement for the raw materials. Production costs were obtained mainly via interviews to three major brick-making factories based in the Ramallah area.

The monthly savings in the production cost is calculated using:

Savings = total production cost (using conventional raw materials) – total production cost (using alternative raw materials).

Figure 9 below outlines the experimental procedure designed to test the technical feasibility of using the sludge and sludge ashes in the manufacture of concrete bricks.

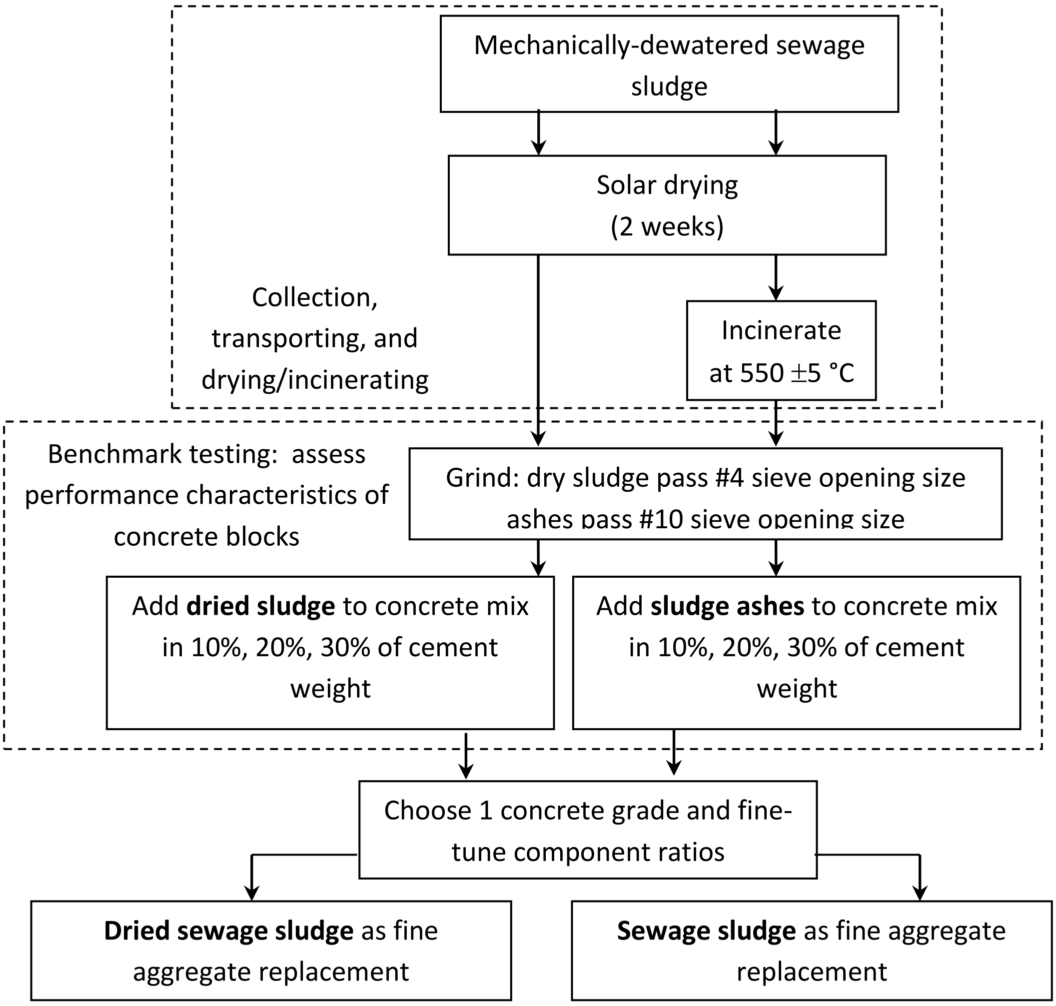


Figure 9 | Flowchart of experimental procedure designed to test technical feasibility

In the first stage, fresh dewatered sewage sludge was collected and transported to the laboratory – a part of it for passive sun-drying and the other part for incineration. The next stage involved manual grinding of both the dried and incinerated samples and then their subsequent incorporation into a set of three pre-designed concrete mixtures (grades M20, M25, and M30) consisting of cement, crushed stone, sand, and tap water. The wastewater sewage sludge was blended into the concrete mixture as an additive - in quantities of 10%, 20%, and 30%. The sludge portions were measured and added as percentages of the weights of cement in each sample.

The effect of the addition of the solids to the concrete mixture is analyzed and an optimum biosolids-amended concrete mixture is selected (one of 0 – 10%, 10 - 20%, or 20 – 30%) based on an acceptable compressive strength value.

The determination of an acceptable strength value was based on reported values of average compressive strength of concrete masonry hollow bricks representing actual tests done for brick-making factories (Table 9) over a period of 1 calendar year. Those test results were obtained from a reputable testing laboratory in the Ramallah area.

Table 9 | Reported compressive strength representing actual tests performed for brick-making factories

Item analyzed	Compressive strength	Specification requirement(3)
CMU(1) 40 x 20 x 10 cm	4.5 – 7.0(2) MPa	3.5 Mpa

(1) Concrete masonry unit (non-load bearing; used for construction of non-load bearing walls and structures)
(2) Adjusted to account for void volume
(3) Palestinian Standards specification 0P01-2010

The lowest value reported is 4.5 MPa which exceeds the specifications by about 30%. The acceptable compressive strength value used in this study is assumed to be the value that exceeds the specification by one-third of that number (i.e. 10%).

After determining an acceptable percentage range for a sludge dosage (both for dried biosolids, and sludge ashes), a similar trial program was set up but this time using sludge and sludge ashes to replace the second most expensive component in the concrete mixture which is sand.

3.3 Materials and methods

The concrete used in this research is a mixture of ordinary Portland cement (OPC), sand (as the fine aggregate), crushed stone (as the coarse aggregate), ordinary tap water, and dewatered wastewater sludge (as solar-dried biosolids, and as incinerated ashes). Control specimens contained all of the mix constituents with the exception of sewage sludge or incinerated sewage sludge ashes.

3.3.1 Portland Cement

According to the ASTM, there are five basic types of Portland cement:

Type I	regular cement for general use
Type II	moderate sulfate resistance
Type III	high early strength because of increase in C_3SiO_2
Type IV	low heat
Type V	high sulfate resistance

Commercially available all-purpose Portland cement (manufactured by Nesher Cement, Inc. of Israel) is used throughout this research. The cement conforms to the ASTM C150 specifications.

The same cement grade is used in typical brick-making factories in Palestine. Figure 10 shows the characteristic compressive strength of the obtained Nesher cement as obtained from the manufacturer's specifications on the website (http://www.nesher.co.il) Once the 50.0 Kg cement bags were opened, they were placed in large plastic bags so as to seal them from contact with air and moisture.

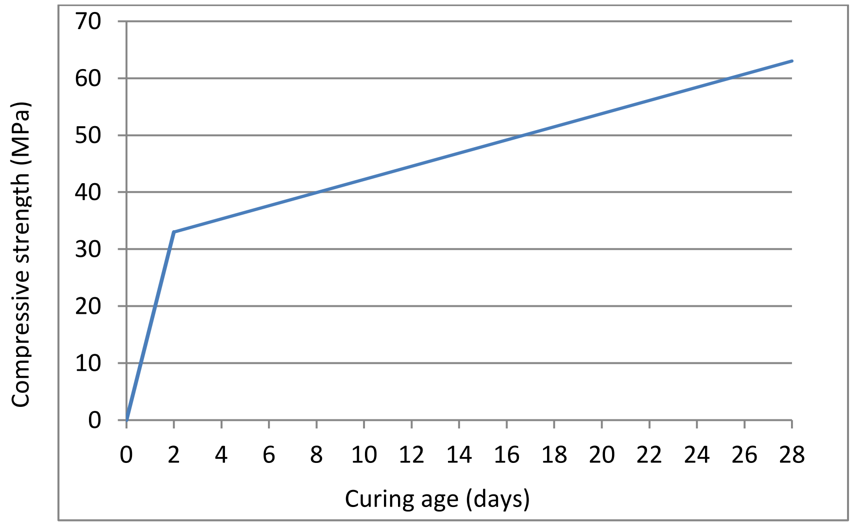


Figure 10 | Nesher concrete compressive strength as a function of curing age (According to the manufacturer's specifications)

3.3.2 Water

Water causes the hydration of the cementitious material to form a cement paste that bonds together the sand and gravel and other components of the concrete to form a hardened solid mass. Throughout his research, regular laboratory tap water of Al-Bireh was used for the cement hydration.

3.3.3 Aggregates

The combination of fine and coarse aggregates (inert materials) make up 70% - 85% of the concrete mass. Their properties (such as type, quality, cleanliness, grading, and moisture content) have a large influence on the concrete's freshly mixed and cured properties, mixture proportions, as well as economy.

3.3.3.1 Physical properties | Relative density

The relative density (specific gravity) of the aggregates is the ratio of its mass to the mass of an equal absolute volume of water. In this work, the relative density value will not be used as an aggregate quality parameter, but only in the computation of the concrete mixture proportioning (Appendix I).

ASTM C128 and ASTM C127 were used in the laboratory to determine the relative densities for fine and coarse aggregates respectively.

3.3.3.2 Physical properties | Absorption capacity and surface moisture

The water absorption of aggregates was determined in the laboratory according to ASTM C127 and ASTM C128.

The aggregate moisture classification (4 states) of aggregates is illustrated in Figure 11.

In theory, the amount of water that is intended to be added to the concrete mixture should be adjusted to account for the water present in the aggregates as per Figure 11 (for example, less water is needed if the aggregates were in the damp/wet state than if they were oven-dried). Otherwise, the water-cement ratio (w/c) will vary - causing the workability and compressive strength to change. In fact, most fine aggregates can maintain a moisture content of 3% and some can even maintain higher moisture content of 8% - which, if not taken into consideration, will cause the w/c ratio (and hence the compressive strength of the cured concrete) to change drastically.

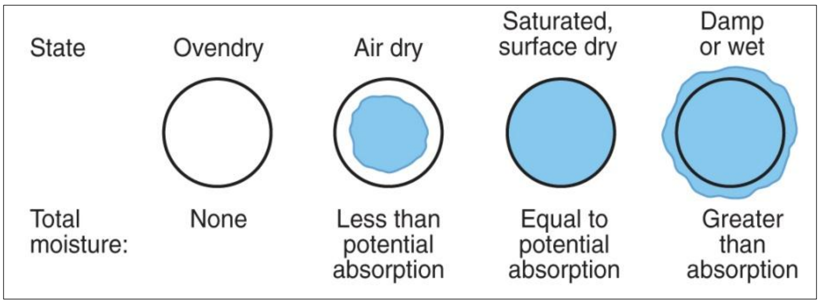


Figure 11 | Four moisture states of coarse and fine aggregates

3.3.4 Wastewater Sewage sludge (dewatered biosolids)

The sewage sludge was collected from the belt-filter dewatering press of Al Bireh wastewater treatment plant (AWWTP) over a period of 6 months. The treatment plant, located 14 kilometers north of Jerusalem, started operation in August of 2000 using an extended aeration system with a mechanical solids handling and a simultaneous aerobic sludge stabilization. Sewage sludge generated at the Al-Bireh wastewater treatment plant is usually thickened, dewatered using an electro-mechanical press filter, and then hauled away to dumping sites. In other words, none of the Al-Bireh produced bio-solids are recycled or re-used for beneficial purposes. Nevertheless, there is increasing interest among researchers at local Palestinian universities to initiate projects and carry out assessment studies that explore the feasibility of putting the generated biosolids to wide applications of beneficial uses.

Table 10 | Design and operating parameters of AWWTP(1)

Description	Criteria
Design capacity	50,000 PE (Expandable to 100,000 PE)
Dry weather daily flow	5750 m^3/d
Dry weather peak hourly flow	480 m^3/h
Rainy weather peak hourly flow	720 m^3/h
BOD (Effluent)	20 mg/l
TSS (Effluent)	30 ml/l
MLSS (aeration tank)	4 g/l
Sludge age	≥ 20 days
F/M ratio	≤ 0.05 kg/kg.d

(1) As reported by the Al-Bireh municipality

Biosolids production at the treatment plant varies depending on the season – with the summer period having the largest quantities of biosolids generated from the thickener tank. According to the plant operators, an average of 500 m^3 of liquid sludge is processed by the belt-press dewatering machines. Under normal conditions, and with an average of 20% solids content, the liquid sludge is reduced by dewatering to a volume of about 100 m^3 on a weekly basis.

3.3.4.1 Sample collection

Dewatered biosolids were not always readily available at the wastewater treatment plant as trucks haul the biosolids away to dumping sites on a regular basis. Thus the municipality of Al Bireh had to be contacted so as to obtain a permission to collect biolsoids samples as well as to coordinate and arrange for a suitable collection day and time.

At the AWWTP, samples were collected at the place where biosolids are stockpiled in large metal containers at the belt-press exit (i.e. point of discharge).

Using a large spatula, 10-12 small grab samples were taken from different biosolids stockpile loads and placed into a stainless container to make one composite sample of total weight of roughly 10 kg. Some stockpiles had formed crusts due to the weathering action – and attention was given so that the samples were taken from below the surface of any crusting formations. The grab samples were then mixed together thoroughly and were subsequently transported to the solar drying location.

Twenty nine (29) other composite biosolids samples (of roughly 10 kg each) were collected in the same manner as described above over a period of six months. According to the AWWTP operator, all the biosolids stockpiles from which the samples were collected were more or less fresh stockpiles and none were more than 2-3 days old.

3.3.4.2 Sample preparation

I. Solar-dried biosolids

Since thermal drying is an energy-intensive process and its associated energy costs could affect the marketability of the final product (i.e. bio-solids-amended bricks), a simple process of open-air and sun (solar) drying was used to further remove the remaining liquid from the grab collected dewatered biosolids cake samples. In solar drying, surface aeration is supplied by means of the wind, and the sludge is heated by the direct exposure to solar radiation. The principle advantages of utilizing this low-technology drying method are attributed to its low cost, infrequent attention required, and high solids content in the dried product. Problem areas include large land requirements, sensitivity to climatic conditions (primarily rainfall, humidity, and snow), and most frequently, offensive odor emissions.

Two open, concrete-paved solar-drying beds (1.5 m^2) that are lined with artificial media (clear polyurethane sheets) were prepared and used to dry the dewatered biosolids samples in batches of roughly 10 kg each (Figure 12). The biosolids batches were weighed and then uniformly spread on each of the two beds to a height of 15 cm and were manually turned using a shovel once every 12 hours so as to enhance the solar drying efficiency. Careful monitoring of the drying beds confirmed that the biosolids batches produced no visible leachate. After 14 days (336 hours) of drying (and turning), the biosolids were uniformly dried from top to bottom. The biosolids' weight was reduced by an average of 90% (i.e. the sludge originally contained about 10% dry solids) to a thickness of roughly 5 mm due to the evaporation of the water from the samples.

Figure 12 | Dewatered sewage sludge sample on solar-drying bed

During the winter months, a closed tunnel-type system was erected to protect the sludge from rainwater while drying (Figure 13). The greenhouse effect provided effective usage of solar energy - thus allowing the inside temperature to be 10 ± 3 °C higher than the outside temperature on average during daytime.

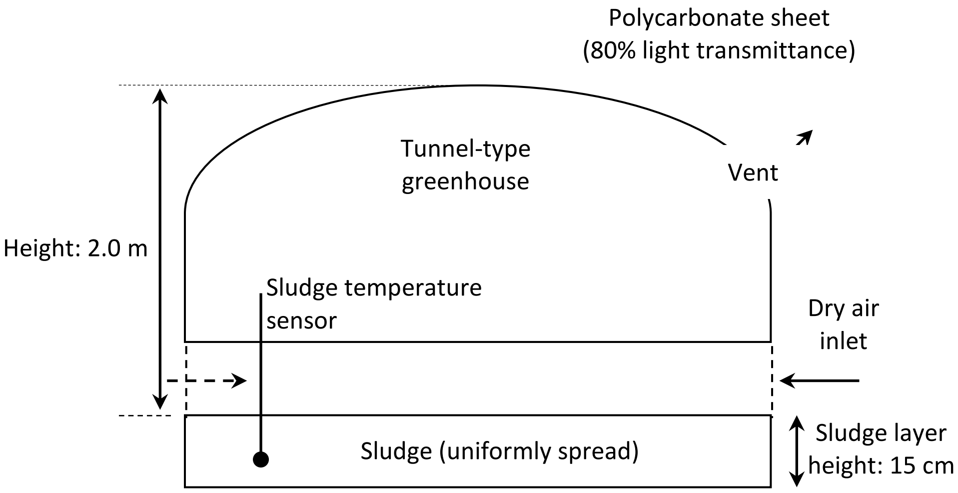


Figure 13 | Schematic view of the tunnel-type greenhouse enclosure for sludge drying

After the manual turning/drying cycle has been completed (i.e. after 14 days and at which the daily change in weight reduction is less than 1%), the biosolids were hard, appeared to have a coarse and porous texture, had a deep dark brown color, and possessed a strong unpleasant and offensive smell (Figure 14).

Figure 14 | Solar-dried wastewater sewage sludge

One grab sample was taken from each of the 2 drying beds to make one composite sample that was placed in a sealed plastic bag and then delivered to the materials lab to be grinded/powdered (using a manual mortar grinder) to the required grain-size and then stored in tight plastic containers awaiting to be incorporated into concrete (Figure 15).

Before grinding After manual grinding

Figure 15 | Solar-dried biosolids

(Total drying period: 14 days | Average daily daytime ambient temperature: 23 °C)

II. Incinerated biosolids (ISSA)

ISSA generally meets the waste acceptance criteria as an inert waste within the meaning of the Waste Framework Directive. No standards currently exist on the use of ISSA in the construction industry.

There are no sewage sludge incinerator plants in operation in the West Bank. As a result, sewage sludge ashes had to be incinerated in the laboratory (Figure 16).

Figure 16 | Laboratory-incinerated wastewater sewage sludge ashes (ISSA)

The incineration process thermally destroys the organic matter in the sewage sludge. Typically, ISSA contain about 25% silicate, 33% calcium oxide, and 20% phosphate (Gunn, 2004).

In functional terms, the incinerated sewage sludge ash could have pozzolanic properties (reactive silica that exhibits cementitious properties when it reacts with calcium hydroxide in the presence of water) which makes it potentially useful as an addition to Portland cement mixtures – as it could increase the long-term strength of concrete (> 28 days) and could reduce the material cost of the concrete.

In order to obtain SSA, to be used as an additive and as a sand replacement, the dewatered sewage sludge was heated in the laboratory in an electric oven at 550 ± 5 °C for 3 hours. Afterwards, the obtained SSA was manually grinded using a manual mortar grinder for 5-7 minutes. The particle size distribution of the resultant fine ashes is presented in Table 11 and Figure 17.

Table 11 | Granulometry of dry sewage sludge and of sewage sludge ash

Sieve Opening Size(1)		**Dry Sewage Sludge**	**Sewage Sludge Ash**
		Gradation (% passing)	**Gradation (% passing)**
4.76 mm	#4 sieve	100%	100%
2.38 mm	#8 sieve	98.5%	100%
2.00 mm	#10 sieve	95.1%	100%
1.00 mm	#18 sieve	89.1%	91.1%
0.85 mm	#20 sieve	69.1%	85.2%
0.42 mm	#40 sieve	49.4%	70.2%
0.21 mm	#70 sieve	39.4%	53.0%
0.149 mm	#100 sieve	15.0%	42.1%
0.074 mm	#200 sieve	4.4%	20.5%
0.037 mm	#400 sieve	--	4.5%
Bulk density		--	2.92 g/cm^3

(1) US Sieve Series

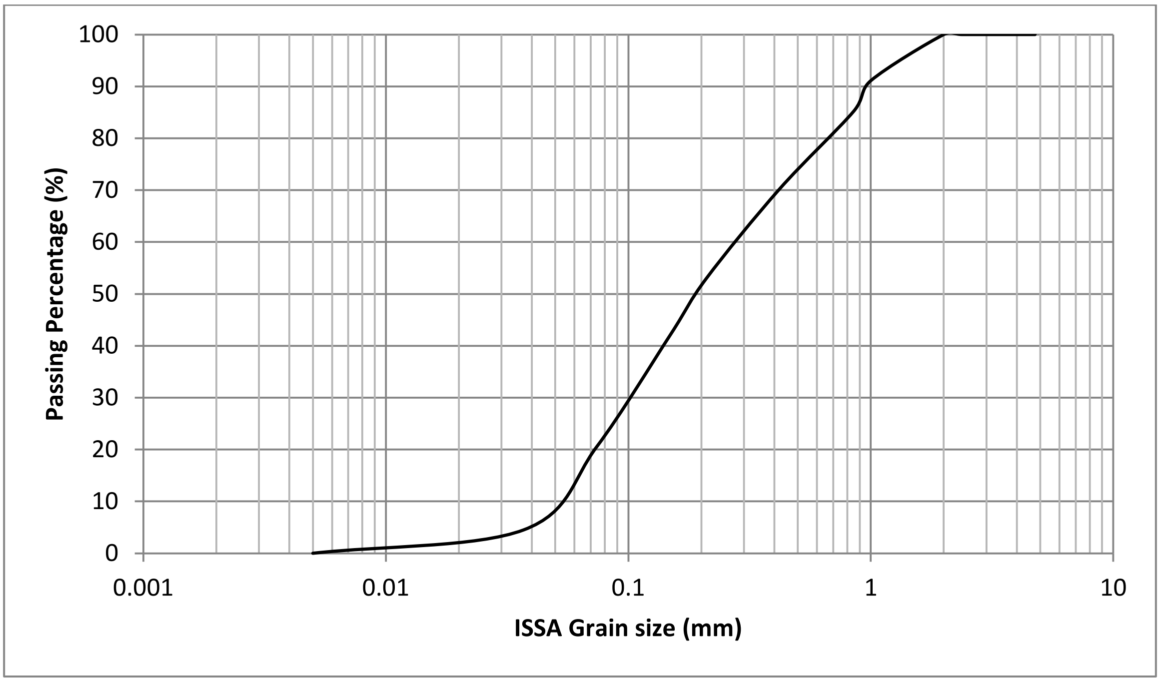


Figure 17 | Particle size distribution curve for the manually grinded SSA

3.4 Experimentation program and testing procedures

3.4.1 Concrete mix design

In order to minimize the cost of production while maximizing the amount of biosolids used, it was desirable to cast concrete bricks containing the highest proportion of biosolids while containing the lowest amount of cement – as cement is the most expensive component of all of the concrete basic mix components.

The mix design procedure must therefore ensure that the minimum required amount of cement is utilized so as to achieve the required final strength (i.e. target strength) of the cured concrete and at the same time, the concrete to act as a stabilizing matrix to the biosolids that were incorporated as an additive. The Indian Standard IS 10262:2009 (Appendix I) was used in this study to create economic (lowest quantity of cement usage) concrete mix designs.

3.4.2 Sample proportioning

In the first step, a benchmark experimentation program was carried out using 3 different concrete mix designs so as to produce 3 different grade types (M20, M25, and M30).

I. Solar-dried wastewater sludge were added in ratios of 10%, 20%, and 30% (biosolids to cement weight) to each of the 3 concrete grade mixtures - making a total of 9 specimen variations. Additional specimens (for each of the 3 grades) are also made as a control sample that did not contain any biosolids (Table 12).

II. Sludge ashes were added in ratios of 10%, 20%, and 30% (biosolids to cement weight) to each of the 3 concrete grade mixtures - making a total of 9 specimen variations. Additional specimens (for each of the 3 grades) are also made as a control sample that did not contain any biosolids (Table 12).

3.4.2.1 Benchmark test: biosolids as additive

This test was performed to identify a rough value of a “threshold ratio” (of biosolids to cement) at which the produced bricks cannot be marketed and thus are not acceptable in terms of one or more of the following performance indicators:

- Physical strength after 7, 28 and 90 days of curing (i.e. to meet the standards set for similar-purpose concrete blocks (Table 9))
- Process efficiency (i.e. workability is not drastically altered so as to affect the bricks manufacturing processes such as clogging of the bricks-making machine)
- Density and compaction (i.e. form finish: produced blocks are fully formed and have smooth sides and the ability of the concrete mix to being molded into components of any shape)

Table 12 | Biosolids-amended mix proportions for benchmark test

Test ID(1)	Concrete Grade	wastewater sludge (% wt of cement)	OPC : sand : crushed stone mix ratios			W/C ratio
			Portland cement	Sand	Crushed stone	
M20-00B-ADD	M20	0%	1	1.5	3	0.52
M20-10B-ADD	M20	10%	1	1.5	3	0.52
M20-20B-ADD	M20	20%	1	1.5	3	0.52
M20-30B-ADD	M20	30%	1	1.5	3	0.52
M20-00B-ADD	M25	0%	1	1.3	2.6	0.45
M20-10B-ADD	M25	10%	1	1.3	2.6	0.45
M20-20B-ADD	M25	20%	1	1.3	2.6	0.45
M20-00B-ADD	M25	30%	1	1.3	2.6	0.45
M20-00B-ADD	M30	0%	1	1	2	0.39
M20-10B-ADD	M30	10%	1	1	2	0.39
M20-20B-ADD	M30	20%	1	1	2	0.39
M20-30B-ADD	M30	30%	1	1	2	0.39
		Sludge ashes (% wt of cement)				
M20-00A-ADD	M20	0%	1	1.5	3	0.52
M20-00A-ADD	M20	10%	1	1.5	3	0.52
M20-00A-ADD	M20	20%	1	1.5	3	0.52
M20-00A-ADD	M20	30%	1	1.5	3	0.52
M20-00A-ADD	M25	0%	1	1.3	2.6	0.45
M20-00A-ADD	M25	10%	1	1.3	2.6	0.45
M20-00A-ADD	M25	20%	1	1.3	2.6	0.45
M20-00A-ADD	M25	30%	1	1.3	2.6	0.45
M20-00A-ADD	M30	0%	1	1	2	0.39
M20-00A-ADD	M30	10%	1	1	2	0.39
M20-00A-ADD	M30	20%	1	1	2	0.39
M20-00A-ADD	M30	30%	1	1	2	0.39

(1) M20: concrete grade | 00B: 0% biosolids 00A: 0% ashes | ADD: biosolids as additive to mixture

Each specimen consisted of three identical bricks (as replicates) made for each of the mix ratios in the benchmark test and the average is calculated for each of the values for the compressive strength of the produced and cured blocks.

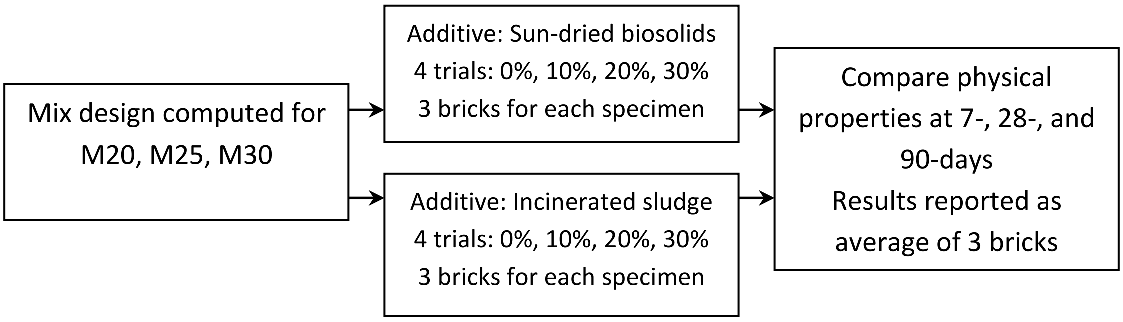


Figure 18 | Methodology for conducting benchmark test – details are listed in Table 12

3.4.2.2 Biosolids and ashes as sand replacement

In this stage, a second experimentation program was designed based on the results of the previous benchmark test (which gave the rough value of the maximum biosolids dose along with the optimal concrete mix design that produced acceptable blocks). The purpose is to fine tune the maximum amount of biosolids and ashes that can be incorporated into concrete while producing acceptable bricks and at the same time holding the resultant ratio of cement:sand:aggregates constant.

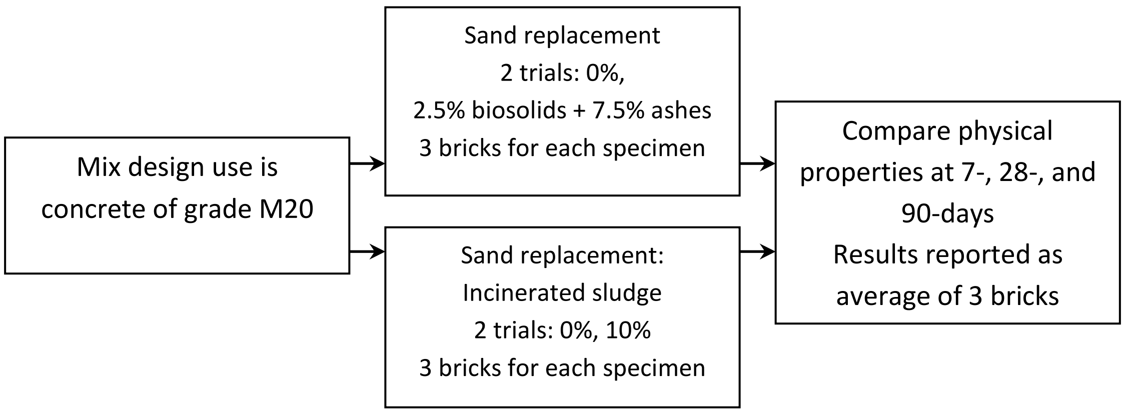


Figure 19 | Methodology for fine-tuning optimum sludge dosage – details are listed in Table 12

Table 13 shows a sample mix proportions for preparing grade M20 concrete. The table shows the quantity of sludge to be added for each trial.

Table 13 | Mass of raw materials and amount of water required per brick mold for different proportions of added sludge (wt %) – Grade M20 concrete

Wastewater Sludge (wt. % of cement)	Mass of raw materials and water as required per brick					
	Portland cement (g)	Sand (g)	Crushed stone (g)	Sun- dried sludge (g)	Mixing water (g)	Total mass of mixture (g)
0 (Control)	386.5	611.1	1199.2	0	201	2398.2
10%	386.5	611.1	1199.2	38.7	201	2436.9
20%	386.5	611.1	1199.2	77.3	201	2475.5
30%	386.5	611.1	1199.2	116.0	201	2514.2

3.4.3 Assessment of the concrete blocks manufacturing technology

Concrete masonry has become a standard building material as it is used to create structures that are economical, energy efficient, fire-resistant, and requires minimal maintenance. The blocks are manufactured in of shapes and sizes, either solid and hollow, dense or lightweight, air-cured or steam-cured, load-bearing or non-load bearing. Many concrete blocks manufacturing processes use pumice aggregates (porous vesicular material) to create lightweight masonry blocks.

The most common sizes that are produced in Palestine are listed in Table 14:

Table 14 | Standard-type CMUs (lightweight) that are produced in the West Bank

Masonry concrete Block dimensions (WxHxL)	Weight (Kg)	Density (Kg/m^3)	Cavities %	Minimum Compressive Strength (Kg/cm^2)	
				Non-load bearing	Load bearing
20 x 20 x 40 cm	14 - 20	875 - 1400	47.8	35	70
15 x 20 x 40 cm	15	667	46.9	35	70
10 x 20 x 40 cm	10	1375	40.2	35	70
7 x 20 x 40 cm	7.5	1428	40.1	35	70
4 x 20 x 40 cm	5	1607	---	35	70

The standard concrete block is a rectangular 20 x 20 x 40 cm produced mainly from Portland cement, gravel, sand, and water and has water absorption of a maximum of 20% of the dry weight of the block.

Some manufacturing plants produce concrete blocks only, while others may produce a wide variety of precast concrete products including blocks, flat paver stones, and decorative landscaping pieces such as lawn edging. The typical production of concrete blocks consists of 3 basic process stages: mixing, molding, and curing (Figure 20). In the molding stage, the machine consolidates and compacts the low-slump concrete mix into the desired shape so that the blocks are uniform in size and attain the desired shape properties.

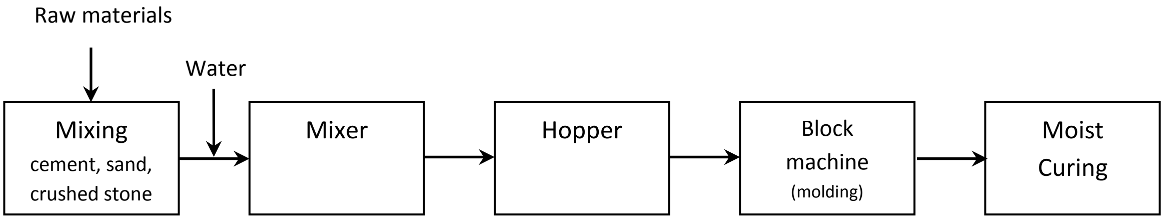


Figure 20| Typical concrete blocks production process stages (used by existing factories)

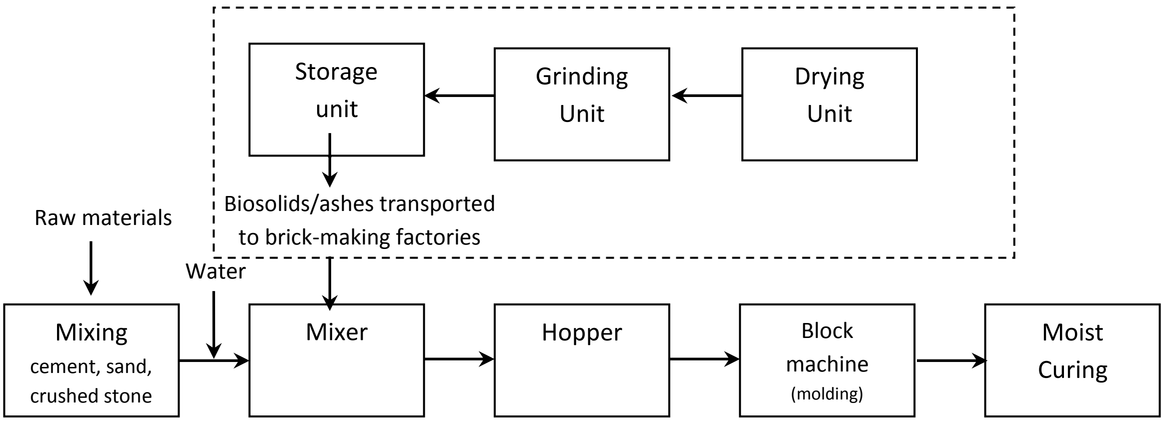


Figure 21| Typical concrete blocks production process stages (no modification is necessary if drying, grinding, and storing biosolids is done at the WWTP)

In order to incorporate solar-dried biosolids or sewage sludge ashes into the concrete blocks manufacturing process, no major or costly modification to the existing process is necessary. The only necessary modification is an additional unit for grinding the sludge. The factory is assumed to have a storage facility on site for the sludge. The solids maybe introduced into the mixing stage after the water has been added to the concrete mix (Figure 21).

3.4.4 Assessing physical properties

Physical properties of the concrete paste (slump) and the cured concrete brick (compressive strength, density, and water absorption) are the basis for the performance criteria for this study.

3.4.4.1 Consistence tolerance (slump)

Workability of fresh concrete consists of two components: consistency and cohesiveness. Consistency describes how easily fresh concrete flows, whereas cohesiveness is the ability of fresh concrete to hold all of the ingredients together uniformly.

In accordance with ASTM C143, the concrete slump test was used to help consistently measure the workability of each of the concrete-sludge mixes (Figure 22). A workable concrete mix properly flows and fills the form properly, leaving minimal voids at the form face and completely surrounding any rebar to create a bond.

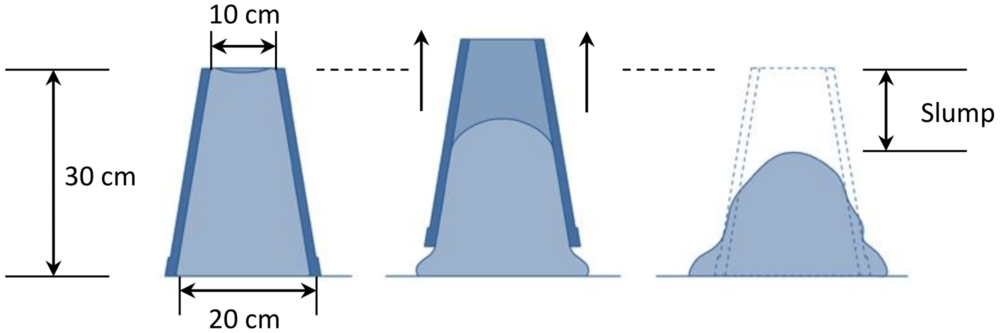


Figure 22 | Determination of hydraulic-cement concrete (fresh) slump value (ASTM C143)

The slump value is recorded by measuring the vertical distance between the top of the mold and the displaced original center of the sample. A collapse slump will generally mean that the mix is too wet or that it is a high workability mix, for which slump test is not appropriate. Very dry mixes, having slump 0 - 25 mm are used in road making while low workability mixes, having slump 10 - 40 mm are used for foundations with light reinforcement.

Table 15 shows the classification of the concrete mix's workability according to slump values. Medium workability mixes of 50 - 90 are used for normal reinforced concrete and placed with vibration.

Table 15 | Concrete slump classification

Class	Slump Range (mm)	Slump Target (mm)	Workability	Maximum Variation Allowed (mm)
S1	10 – 40	20	Low	-20 to +30
S2	50 - 90	70	Medium	-20 to +30
S3	100 – 150	120	Medium-High	-20 to +30
S4	160 - 210	170	High	-20 to +30
S5	220+	220+	---	---

All the slump tests were carried out in a controlled laboratory environment. The metal mold was dampened and placed on a steel plate. The mold was filled up to one-third with biosolids-amended wet concrete mix. Using a rod, the bottom layer of the concrete mix was hit with 25 strokes. Next, additional concrete was added to fill two-thirds of the mold and the concrete mix was hit with another 25 strokes using the rod while penetrating the 2 layers. A third layer was added and the rod was used again penetrating the top and second layers only. The mold was then inverted and the slump value was measured and recorded as shown in Figure 23.

Figure 23 | Consistence tolerance testing for biosolids-amended concrete mix (lab images)

The concrete mixes that were used in the consistence tolerance testing (slump) were discarded and fresh mixes were used to fill the cube molds.

3.4.4.2 Compressive strength

Concrete mixtures can be designed to provide a wide range of mechanical and durability properties in order to meet the design requirements of a given structure. Compressive strength is the most common performance measure and is calculated by dividing the failure load by the cross section area resisting the load. It can be a representative to assess the overall quality of hardened concrete. Concrete compressive strength can vary between 2500 psi (17 MPa) for residential concrete to 4000 psi (28 MPa) in commercial structures. Higher strengths of up to and exceeding 10,000 psi (70 MPa) can be achieved to fulfill certain design criteria. In most cases, strength requirements for concrete are at a curing age of 28 days.

All cube specimens were prepared by filling each double-mold up to a third full with biosolids-amended concrete wet mix using a scoop (Figure 24 – 2 top images). Utilizing a compacting rod (Figure 24 – image 3), the concrete was compacted with uniform strokes to up to 30 times while adding more concrete to fill the molds to the top. Using a rubber-covered hammer, the metal molds were tapped at their sides so as to ensure there are no air voids left (not shown). The last step was to compact-finish the surface of the wet concrete utilizing a trowel and any excess concrete from the mold was discarded.

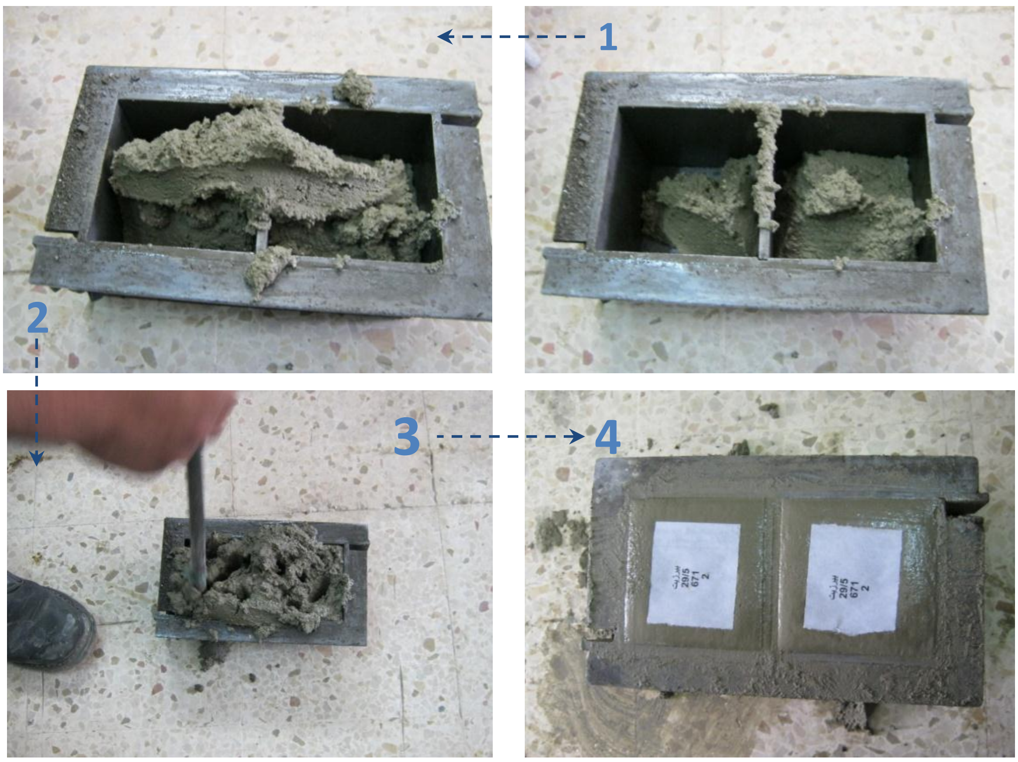


Figure 24 | Molding steps of biosolids-amended cubes (10 mm x 10 mm x 10 mm) – @ Ramallah Laboratory

Figure 25 | Biosolids-amended specimens (10 x 10 x 10 cm blocks) are being taken placed in a water curing bath

Individual cube specimens were numbered, date-identified and were then covered to avoid water evaporation. The cube specimens were stored in the lab at a temperature between 20 and 30 °C for 24 hours after which they were de-molded and then transferred to a temperature-controlled water bath awaiting the 7-day testing (Figure 25).

The water-cement ratio (w/c) has an important influence on the quality of concrete produced. A lower water-cement ratio leads to higher strength and durability, but may make the mix more difficult to place. Figure 26 shows a relationship of the compressive strength of concrete as a function of the curing age under different curing conditions.

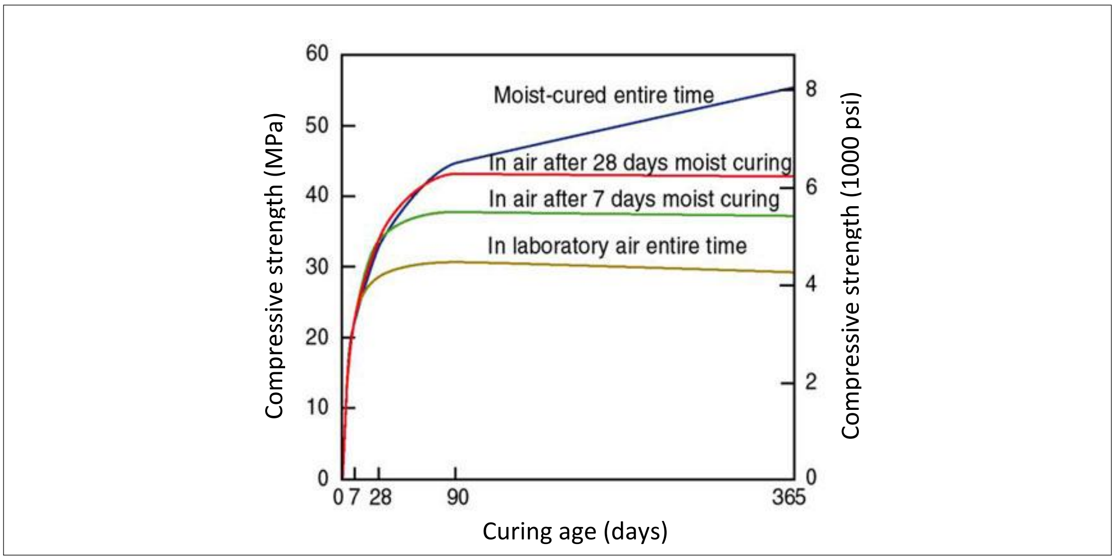


Figure 26 | Concrete compressive strength as a function of curing age (Kosmatka, Kerkhoff, & Panarese, 2008)

As a rule of thumb, for every 1% increase in the quantity of water added, the concrete strength is reduced by 5%. As can be seen in Figure 27, following the addition of 20 liters of excess water per cubic meter of concrete, the final achieved strength may be as low as 50% of the desired strength. Furthermore, the concrete will be much more susceptible to early-age drying shrinkage cracking reducing durability and resistance to surface abrasion.

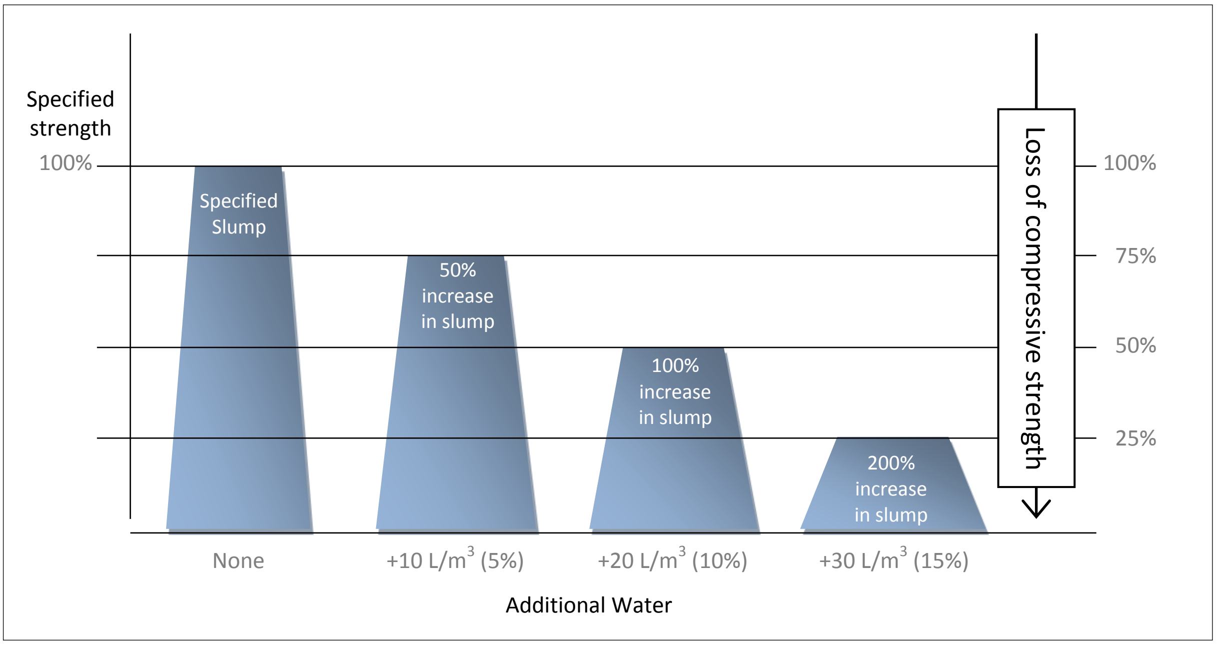


Figure 27 | Effect of uncontrolled addition of water on concrete strength and slump

The addition of water on-site to concrete mixtures has been a controversial topic for as long as concrete has been used in construction. ASTM C94 does allow for a one-time on-site addition of water to adjust fresh concrete properties as long as the maximum specified water-cement ratio is not exceeded (ASTM C94).

Error! Reference source not found. shows the state-of-the-art testing machine that was sed in the testing of most of the specimens. The machine is fully computerized and the compressive strength results are automatically computed and recorded.

The cube specimens were pressure-loaded (without shock) at a constant rate of 0.63 MPa/s.

Figure 28 | Computerized testing of compressive strength of biosolids-amended specimens

Figure 29 shows a sludge-amended block fracture (failure) as the loading pressure of the compression machine had exceeded the bearing capacity of the block

.

Figure 29 | Concrete block fracture and failure under pressure

3.4.4.3 Water Absorption

Low water absorption is one of the most critical properties of good quality concrete blocks. A concrete block with low water permeability resists the absorption of water and the brick is thus less susceptible to freezing and thawing. The less the amount of water than can infiltrate into the brick structure, the higher is the durability of the brick and the higher is the resistance to the weathering conditions.

For the concrete pavers and for concrete masonry units (CMUs), the absorption testing procedure involves drying the block specimens at a temperature of 105±5 °C for 72±2 hours. The dried concrete blocks are cooled to room temperature and then fully immersed in a water bath for 72 ± 2 hours. After the specimens are taken out of the water, the surface moisture is dried utilizing a dry towel. The increase in weight as a percentage of the original dry weight is expressed as the absorption percentage. ASTM C140 specifies that the average absorption of the test samples shall not be greater than 5% and with no individual unit greater than 7%.

It is important to note that concrete water absorption by immersion is not a reliable performance parameter for the estimation of the concrete durability as it only gives an estimation of the total pore volume of the concrete (G. De Schutter, 2004).

3.4.4.4 Density

Concrete mixtures can be manipulated to produce end product concrete with varying densities and can range from 1500 to 2400 Kg/m^3. Lightweight concrete masonry blocks use pumice, a very lightweight mineral, as part of the coarse aggregate in the ingredients.

In this study, the density was determined by directly measuring the unit weights of each of the dry 10x10x10 mm cube specimens before they were loaded into the compression machine.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The effect of organic substances on the setting time of Portland cement and on the ultimate strength of cured concrete is a challenge of considerable complexity. This chapter presents the laboratory results of various physical properties of hardened concrete blocks that have been amended with biosolids and sludge ashes namely physical strength, consistence tolerance, water absorption, and density.

A benchmark test was first carried out to gauge an estimate range of biosolids to cement ratio at which a set of performance indicators are met. The results outline the effect of the addition of sun-dried biosolids on the slump value of the concrete paste as well as on the compressive strength, water absorption, and density of the hardened concrete.

4.2 Compressive strength

The compressive strengths of 12 different hardened concrete specimens are presented in Table 16 - 18, tested at 7-, 28-, and 90-day curing age. In all the runs, the cubes' dimensions were 10 cm x 10 cm x 10 cm. There were no discrepancies in the lengths, widths, or heights of any of the produced cubes as the concrete was cast in 12 identical iron-made molds.

4.2.1 Control Samples (Free from biosolids/ashes)

For each of the M20, M25, and M30 grades concrete, 3 cubes of standard 10 cm x 10 cm x 10 cm were prepared (making a total of 9 blocks). Their average compressive strengths were tested and recorded at ages of 7-, 28-, and 90-day curing age. The relative compressive strengths of each of the concrete grades were calculated (Appendix III) and they were plotted against the laboratory curing period (Figure 30). Visual inspection of the controls showed that they all had right-angled sides and contained no cracks. Average compressive strength results show that their strength development was typical and gaining about 80 – 90% of the final strength on day 28 of the curing age.

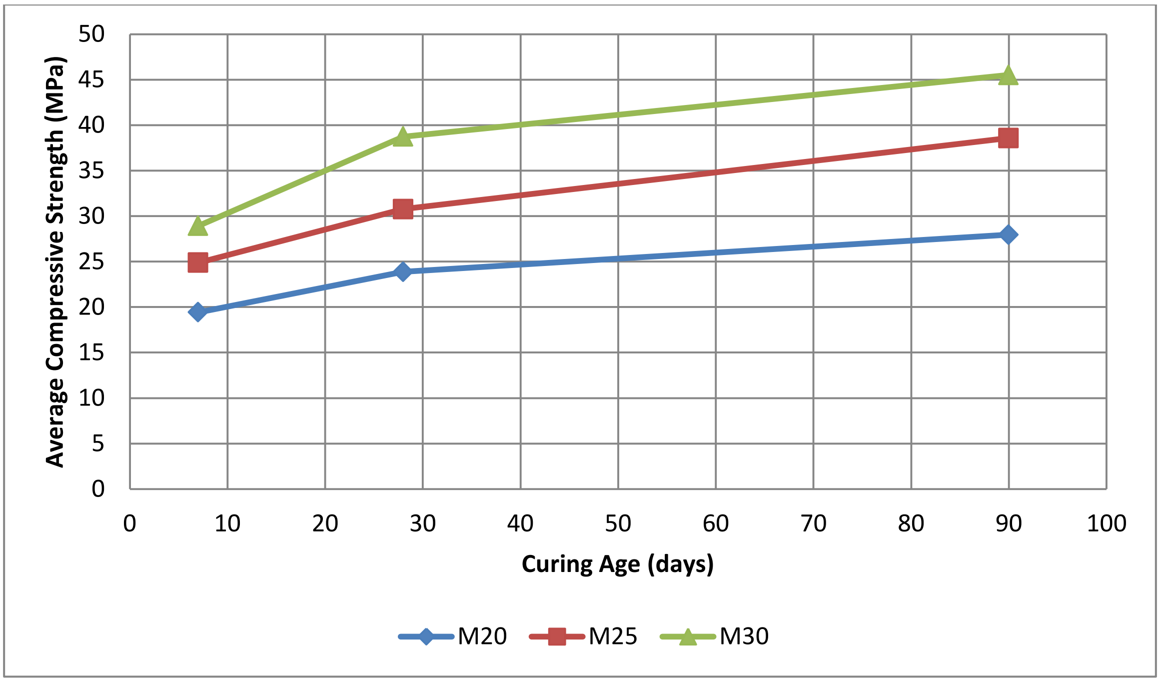


Figure 30 | Relationship between compressive strength and the curing age of the control samples for grade M20, M25, and M30 concrete

4.2.2 Samples containing sun-dried biosolids

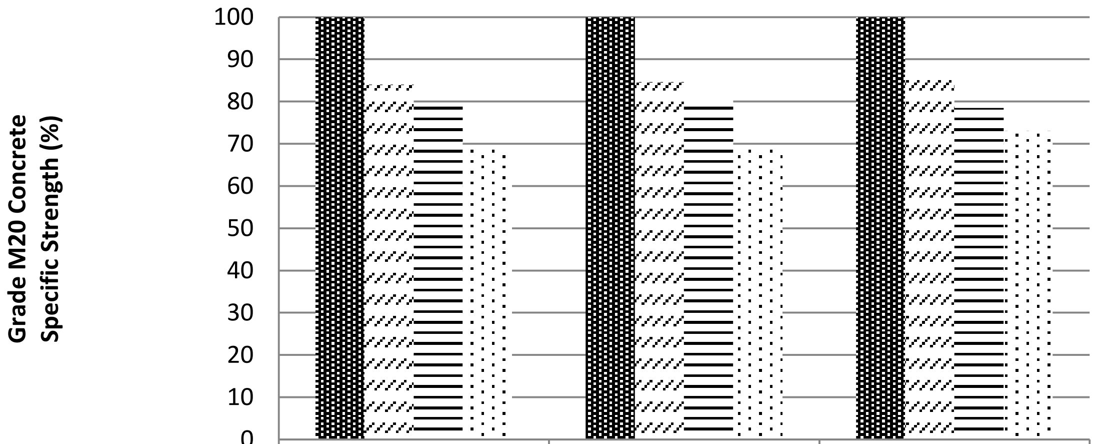
Table 16 outlines the average compressive strength results for grade M20 concrete for 3 different sun-dried biosolids additions (i.e. 10%, 20%, and 30% dried sludge as an additive and measured as percentage weight of cement) recorded at 7-, 28-, and 90-day curing ages.

Table 16 | Average compressive strength of M20 concrete as a function of biosolids added

Test ID	Sun-dried wastewater sludge (% wt of cement)	Concrete Grade	Average compressive strength of cubes (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M20-00B-ADD	Control (0%)	M20	19.42	23.87	27.32
M20-10B-ADD	10%	M20	16.32	20.21	23.76
M20-20B-ADD	20%	M20	15.39	19.19	21.45
M20-30B-ADD	30%	M20	13.43	16.39	19.96

To better analyze and understand the effect of adding dried biosolids to the concrete mixture, the specific compressive strength values are calculated and graphically shown in Figure 30. When compared to the control sample (specific strength 100%), results clearly show that there is an inverse relationship between compressive strength and the quantity of dried biosolids added. On the 7th day of curing, the samples containing 30% biosolids showed weakened strength by as high as 30%. Samples containing 10% dried biosolids showed a decrease in compressive strength by about 13% on day 90 (Figure 31).

The decrease in compressive strength was expected - as the organic material present in the biosolids interfere with the hydration reactions and weaken the cement bonding. Furthermore, organic materials continuously undergo biodegradation and further contribute to the weakening.



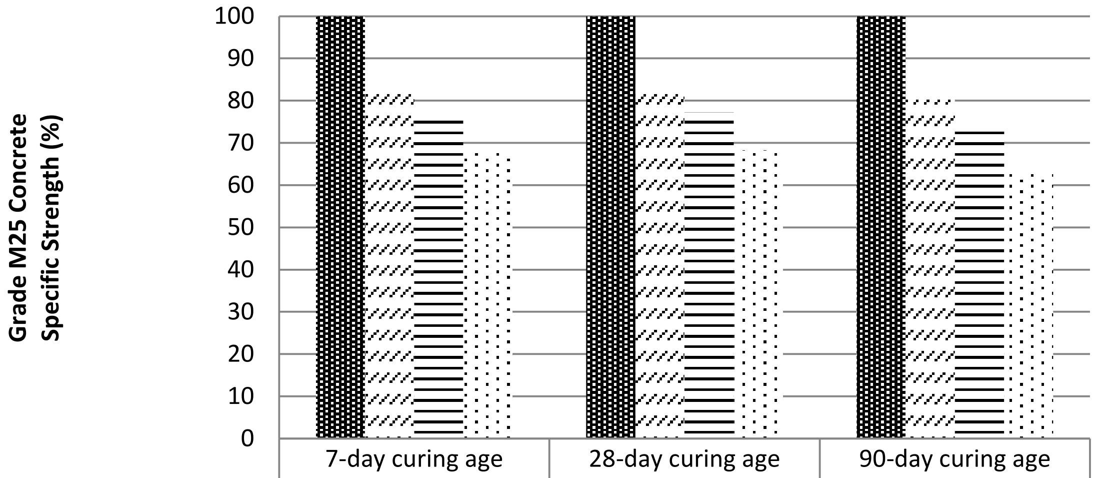
	7-day curing age	28-day curing age	90-day curing age
Control (Sludge Free)	100	100	100
10% Dried Biosolids	84.04	84.67	86.97
20% Dried Biosolids	79.25	80.39	78.51
30% Dried Biosolids	69.16	68.62	73.06

Figure 31 | Specific strength of M20 concrete as a function of the percentage of dried biosolids added

Table 17 shows the average compressive strengths of a higher grade concrete (i.e. M25). When compared to the control sample, the cubes showed a maximum of 37% decrease in strength on day 90 and a minimum of 17% decrease in strength on day 90. Again, results shows that the addition of biosolids has a detrimental effect on both the early age and final strengths of cured concrete (Figure 32).

Table 17 | Average compressive strength of M25 concrete as a function of biosolids added

Test ID	Sun-dried wastewater sludge (% wt of cement)	Concrete Grade	Average compressive strength of cubes (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M25-00B-ADD	Control (0%)	M25	24.87	30.77	38.57
M25-10B-ADD	10%	M25	20.32	25.83	30.96
M25-20B-ADD	20%	M25	19.11	23.75	28.72
M25-30B-ADD	30%	M25	16.83	21.01	24.26



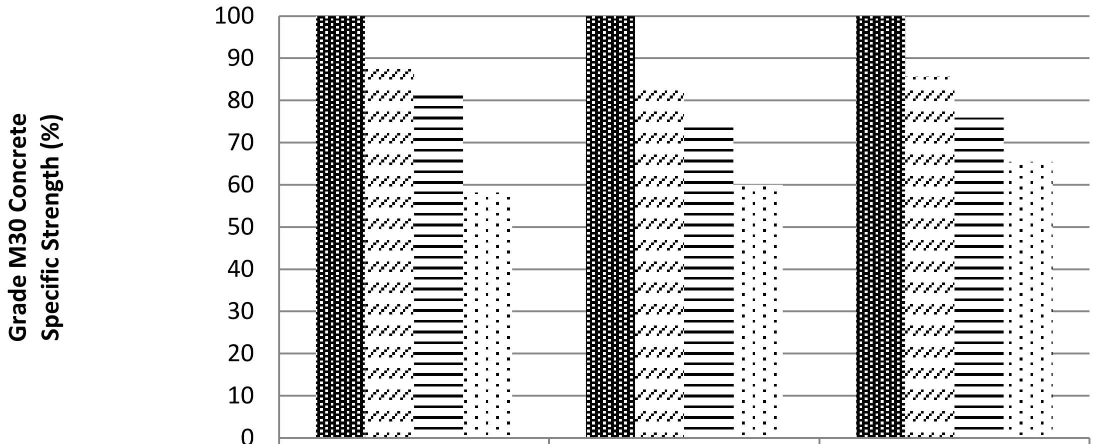
	7-day curing age	28-day curing age	90-day curing age
Control (Sludge Free)	100	100	100
10% Dried Biosolids	81.70	83.95	80.27
20% Dried Biosolids	76.84	77.19	74.46
30% Dried Biosolids	67.67	68.28	62.90

Figure 32 Specific strength of M25 concrete as a function of the precentage of dried biosolids added

Table 18 shows M30 concrete strength characteristics when being amended by dried biosolids. The maximum damaging effect occurred by adding 30% biosolids and resulted in about 40% decrease in the average compressive strength on day 7. The strength on day 90 slightly improved and increased, but still the strength-retarding effect is clear (Figure 33).

Table 18 | Average compressive strength of M30 concrete as a function of biosolids added

Test ID	Sun-dried wastewater sludge (% wt of cement)	Concrete Grade	Average compressive strength of cubes (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M30-00B-ADD	Control (0%)	M30	28.92	38.74	45.40
M30-10B-ADD	10%	M30	25.34	32.12	38.87
M30-20B-ADD	20%	M30	23.87	28.55	34.45
M30-30B-ADD	30%	M30	19.27	23.23	29.71



	7-day curing age	28-day curing age	90-day curing age
Control (Sludge Free)	100	100	100
10% Dried Biosolids	87.62	82.91	85.62
20% Dried Biosolids	82.54	73.70	75.88
30% Dried Biosolids	58.20	59.96	65.44

Figure 33 | Specific strength of M30 concrete as a function of the precentage of dried biosolids added

All previous results show that even though the biosolids were dried for 2 weeks, still their organic content had a negative impact on the compressive strength of cured concrete. This is expected – as the organic material in the biosolids interferes with the bonding process by coating the aggregates and hindering the bonding between the aggregate and the cement.

It is imperative to compare the effect of the addition of sewage sludge on the different grades of concrete. The effect can be clearly demonstrated when a considerable quantity of dried sludge (i.e. 30%) is added to the mixture. One would think that the biosolids addition would not affect the degree of decrease of compressive strength when comparing concretes with different grades. Figure 34 shows that it does. In fact, the chart shows that there a general decreasing trend of compressive strength as the concrete grade is increased. This can be explained by considering the w/c ratio of each mixture.

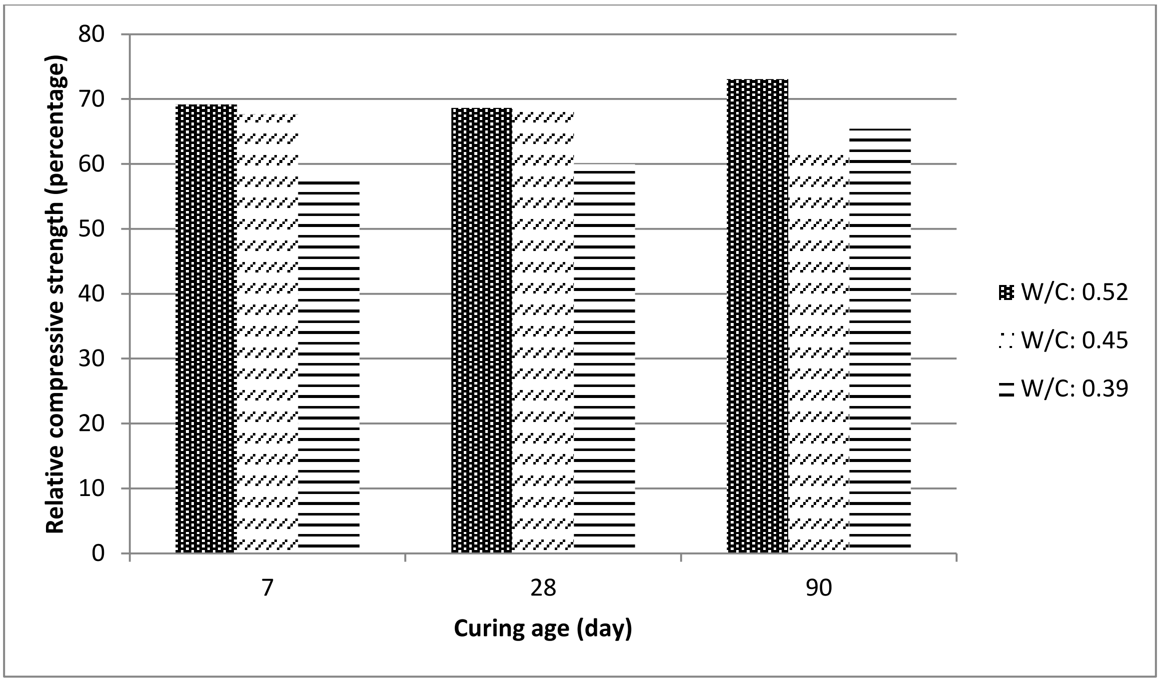


Figure 34 | Comparing relative strengths of grade M20, M25, and M30 concrete (with 30% dried sludge addition)

Theoretically, the strength of concrete is inversely proportional to the amount of water added (or the w/c ratio) – i.e. higher grades of concrete typically have lower w/c values. The results in this report show that the relationship is proportional. This is because the high quantity of biosolids will absorb more water and thus “starve” the mix leaving a partial amount of cement un-hydrated. This results in decreased strength.

4.2.3 Concrete samples containing incinerated biosolids (ashes)

Incinerated biosolids (sewage sludge) contain no organic matter. Furthermore, laboratory tests show that it can be considered as a neutral inorganic material as it has a pH value of about 7.0. In this experimentation program, sewage sludge ashes were used as additive to concrete mixtures.

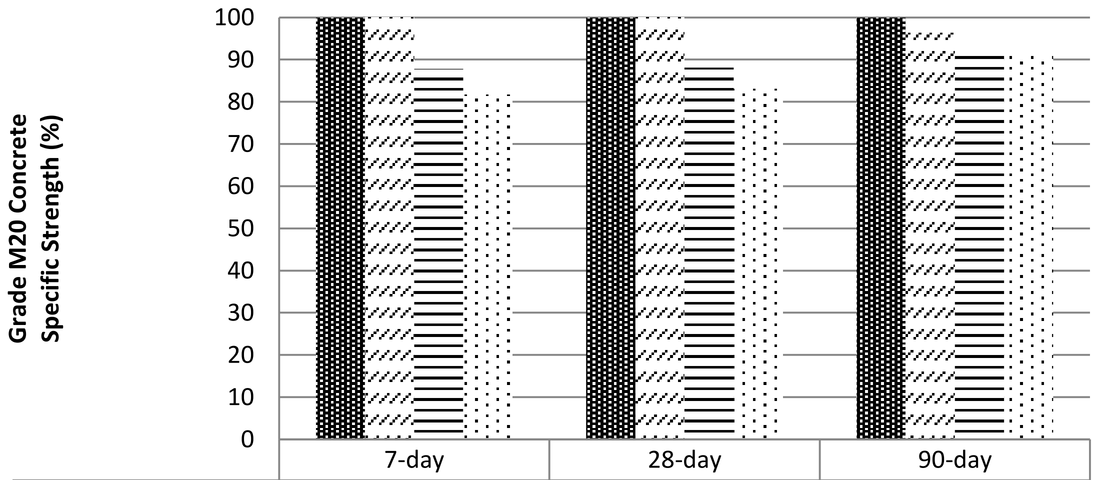
Table 19 shows the average compressive strengths of cured concrete blocks as a result of adding 10%, 20%, and 30% of incinerated biosolids as an additive to the concrete mixture.

Table 19 | Average compressive strengths for SSA-amended concrete cubes

Test ID	wastewater sludge ashes (% wt of cement)	Concrete Grade	Average compressive strength (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M20-00A-ADD	Control (0%)	M20	19.42	23.87	27.32
M20-10A-ADD	10%	M20	19.94	24.01	26.33
M20-20A-ADD	20%	M20	17.06	21.04	24.15
M20-30A-ADD	30%	M20	15.88	19.85	24.90

Specific strengths results for grade M20 concrete are shown in Figure 35. Results indicate that the addition of 10% of biosolids ashes to the concrete mixture had no significant effect on the 7- and 28-day compressive strengths. The compressive strength at age 90 days is reduced by 4%. When the percentage of biosolids ashes was increased to 20%, the blocks' strength development was reduced at the 7-, 28-, and 90-day curing age.

The addition of 30% biosolids' ashes had a more considerable negative effect on the 7th and 28th curing ages. This can be explained by the fact the the SSA is occupying a considerable volume of the block and in turn partially replacing a quantity of the raw materials particularly cement.



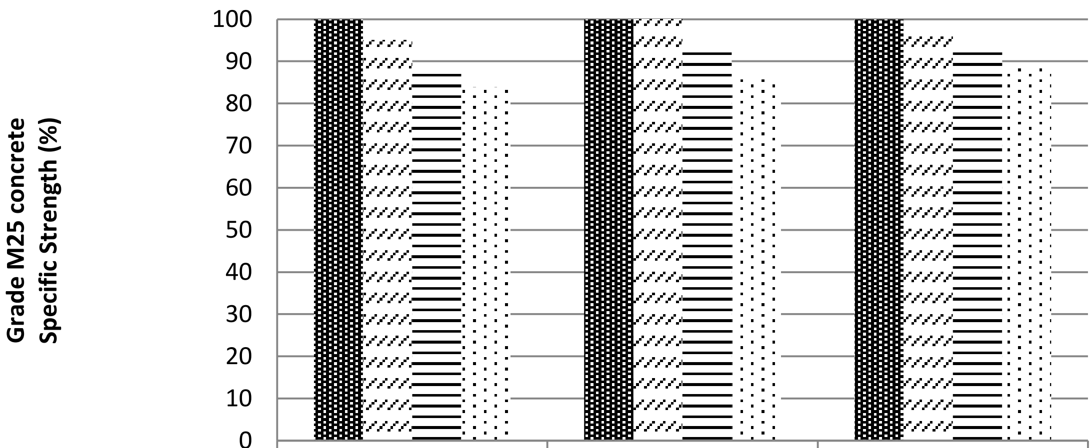
	7-day	28-day	90-day
Control (Sludge Free)	100	100	100
10% SSA	102.68	100.59	96.38
20% SSA	87.85	88.14	91.91
30% SSA	81.77	83.16	91.14

Figure 35 | Specific strengths of ashes-amended concrete cubes at different curing ages for M20 grade concrete

Again, adding sludge ashes to a higher grade concrete mix still has an overall effect of retarding the strength of cured concrete. This is clearly seen from Table 20 and Figure 36. However, the addition of as much as 10% of ashes does not significantly affect strength.

Table 20 | Average compressive strengths for SSA-amended concrete cubes (Grade: M25)

Test ID	wastewater sludge ashes (SSA) (% wt of cement)	Concrete Grade	Average compressive strength (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M25-00A-ADD	Control (0%)	M25	24.87	30.77	38.57
M25-10A-ADD	10%	M25	23.66	31.23	37.70
M25-20A-ADD	20%	M25	22.04	28.50	36.22
M25-30A-ADD	30%	M25	20.87	26.53	34.21



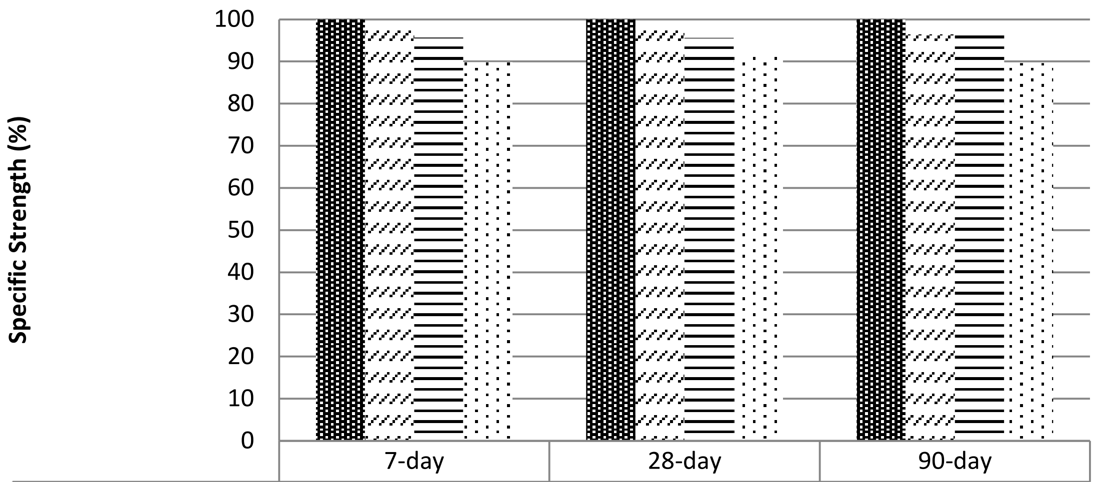
	7-day	28-day	90-day
Control (Sludge Free)	100	100	100
10% SSA	95.13	101.49	97.74
20% SSA	88.62	92.62	93.91
30% SSA	83.92	86.22	88.70

Figure 36 | Specific strengths of SSA-amended concrete cubes at different curing ages for various SSA dosing ratios (as % wt. of cement)

The final test shows the compression results of the incorporation of 10, 20, and 30% sludge ashes in a grade M30 concrete mix (Table 21). The effect is an overall decrease in strength development across the entire curing period. However, the strength is not significantly affected by adding 10% of sludge ashes (Figure 37).

Table 21 Average compressive strengths for SSA-amended concrete cubes (Grade: M30)

Test ID	wastewater sludge ashes (SSA) (% wt of cement)	Concrete Grade	Average compressive strength (MPa)		
			Age: 7 days	Age: 28 days	Age: 90 days
M30-00A-ADD	Control (0%)	M30	28.92	38.74	45.40
M30-10A-ADD	10%	M30	28.22	38.09	43.78
M30-20A-ADD	20%	M30	27.65	37.01	43.98
M30-30A-ADD	30%	M30	25.98	35.32	40.65



	7-day	28-day	90-day
Control (Sludge Free)	100	100	100
10% SSA	97.58	98.32	96.43
20% SSA	95.61	95.53	96.87
30% SSA	89.83	91.17	89.54

Figure 37 | Specific strengths of SSA-amended M30 concrete cubes at different curing ages for various SSA dosing ratios (as % wt. of cement)

4.3 Consistence tolerance

The consistency and cohesiveness (collectively known as the workability) of the fresh concrete mixtures that were amended with sewage sludge and sewage sludge ashes were examined utilizing simple laboratory slump tests. The main factors affecting slump are the water and the additives proportions in the concrete mixture. Typically, increasing the water proportion in concrete mixes results in improved workability (i.e. higher slump value) of the paste. However, this is not recommended since the increase in water quantity will result in a decrease in strength development.

In this study, and as seen in Table 22 and Table 23, the addition of sewage sludge or sewage sludge ashes to concrete mixtures resulted in water-reducing effects in the concrete paste mixtures. This is reflected in reduced slump readings especially when using dewatered and dried biosolids (Figure 38).

Table 22 | Consistency and cohesiveness (workability) of the concrete paste as a function of various sludge proportions (as additives)

Sun-dried wastewater sludge (% wt of cement)	Average slump readings (mm)		
	Grade: M20	Grade: M25	Grade: M30
Control (0%)	72	70	70
10%	65	65	63
20%	60	55	55
30%	50	50	45

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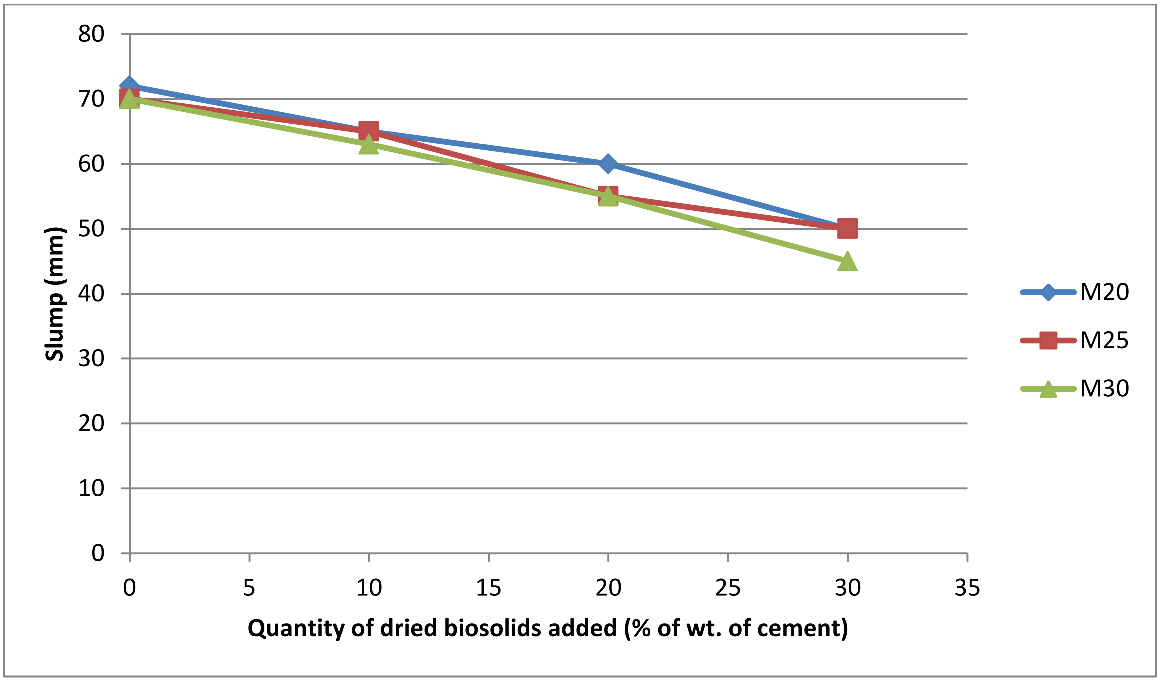

Figure 38 | Slump as a function of the quantity of dried biosolids added

Most brick-fabrication processes employ automatic or semi-automatic operated machinery for the mixing and molding portions of the brick-making processes. Working with concrete mixtures of acceptable workability is critical to the efficient operation of the machines. Mixtures of low slumps can cause frequent machine clogging and thus reduced process efficiency.

Table 23 | Consistency and cohesiveness (workability) of the concrete paste as a function of various sludge ash proportions (as additives)

Sewage sludge ashes (% wt of cement)	Average slump readings (mm)		
	Grade: M20	Grade: M25	Grade: M30
Control (0%)	72	70	70
10%	70	70	65
20%	65	65	55
30%	60	55	55

However, the results from Table 22 and Table 23 show that slump values of concrete pastes having sewage sludge and sewage sludge ashes of up to 10% are not significantly affected and thus are well within the working and acceptable range of typical concrete mixes.

4.4 Water absorption

Table 24 below shows the results of the water absorption test of the produced sludge-amended concrete specimens for each mix after 28 days of curing. As illustrated in Figure 39, the value of water absorption is directly proportional to the quantity of the biosolids or ashes incorporated.

Table 24 | Water absorption capacity for sewage sludge amended concrete bricks

Mix #	Solar-dried wastewater sludge (% wt of cement)	Average water absorption @ a curing age: 28 days	Mix #	Wasterwater sewage sludge ashes (% wt of cement)	Average water absorption @ a curing age: 28 days
M20-00B-ADD	Control (0%)	4.32%	M20-00A-ADD	Control (0%)	4.22%
M20-00B-ADD	10%	4.59%	M20-00A-ADD	10%	4.37%
M20-00B-ADD	20%	9.52%	M20-00A-ADD	20%	5.44%
M20-00B-ADD	30%	15.32%	M20-00A-ADD	30%	7.88%

Concrete specimens containing more than 10% of dried biosolids exhibited a higher percentage of water absorption when compared to the control samples. This indicates that water was being absorbed by both the concrete and the biosolids even though the sludge is trapped within the concrete lattice.

Table 25 shows the accepted standards for water absorption rates of typical concrete cubes.

Table 25 | Maximum water absorption level according to ASTM C90

	Concrete Type		
	Normal	Medium	Lightweight
CMU density (Kg/m^3) – ASTM C33	> 2000	1680 – 2000	< 1680
Maximum Absorption Limit (Kg/m^3)	208	240	288
Maximum Absorption Limit (%)	10.4	10.4 – 14.3	17.1

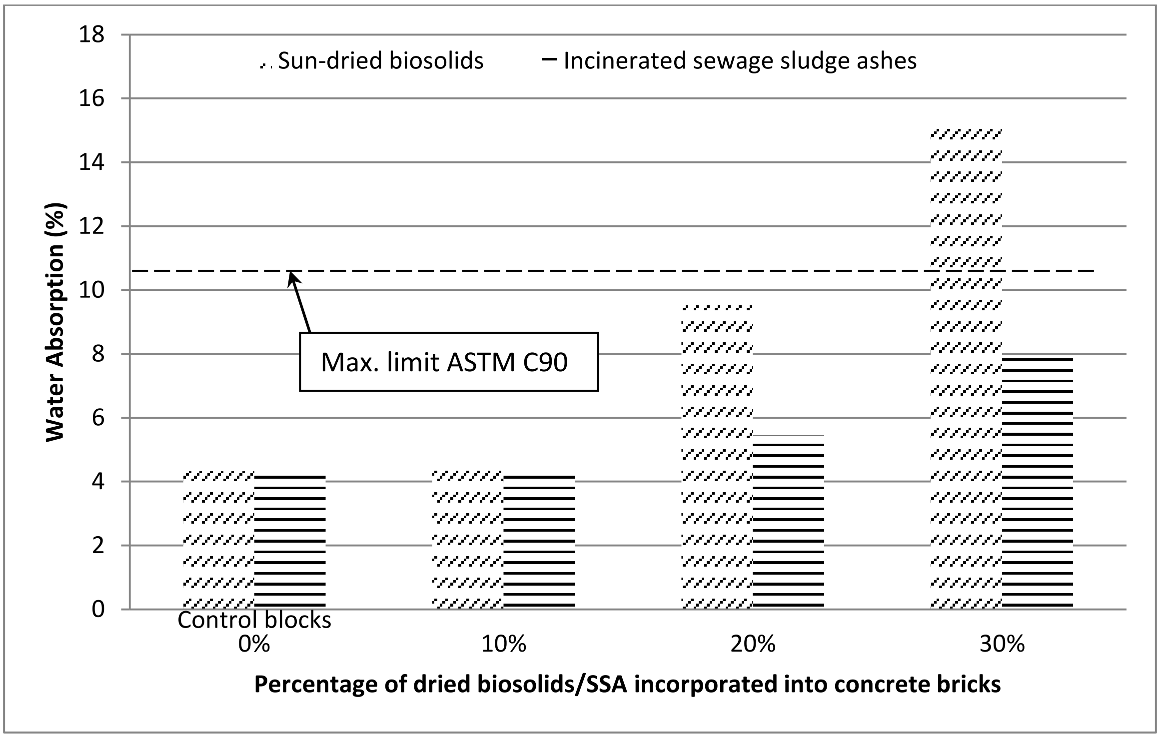

Figure 39 | Water absorption percentage in relation to the amount of sewage sludge incorporated

With the exception of samples containing 30% dried sewage sludge, the water absorption of all the specimens was well within the technical specifications (for the maximum water absorption) for locally produced concrete masonry units in the West Bank.

4.5 Density

The density of concrete masonry units can range from 1500 (lightweight concrete) to 2500 Kg/m^3. Throughout this study, trials were carried out to produce high density concrete on the order of 2200 to 2400 Kg/m^3. Concrete made with lightweight aggregates (to produce low-density blocks) is much more expensive than ordinary-eight concrete.

The average density of the control samples are presented in Table 26. No considerable or significant change in the density of the control blocks was seen across the 7 to 90 days of curing.

Table 26 | Average densities of the control concrete blocks

Control grade designation	Average density (g/cm^3)		
	Curing age: 7 days	Curing age: 28 days	Curing age: 90 days
M20	2.398	2.420	2.428
M25	2.409	2.398	2.422
M30	2.421	2.405	2.431

Table 27 lists the average density values for concrete amended with dried sewage sludge. When compared to the control blocks, there was a noticeable reduction in the densities as the quantity of the sludge was increased. The highest density decrease, ranging from 3 to 5%, occurred in the cube samples that contained 30% of biosolids. This can be attributed to an increased porosity of the cured concrete lattice as a result of the incorporation of wastewater sludge.

Table 27 | Average densities of grade M20 sludge-amended concrete blocks

Mix ID	Sun-dried wastewater sludge (% wt of cement)	Average density (g/cm^3)		
		7 days	28 days	90 days
M20-00B-ADD	Control (0%)	2.398	2.420	2.428
M20-10B-ADD	10%	2.355	2.349	2.332
M20-20B-ADD	20%	2.327	2.320	2.325
M20-30B-ADD	30%	2.319	2.321	2.311

Low-density concrete is desirable for many applications in the construction industry as long as it meets the desired durability and strength criteria. One of the main advantages of using lightweight concrete is its higher thermal insulation than typical concrete. Therefore, the resultant decrease in the density of the sludge amended-blocks can be beneficial in many construction applications.

The same density decreasing trend occurred in blocks amended with sludge ashes. The density decreased noticeably as the sludge quantity was elevated. However, there was no significant change in density for each block sample across the 7 to 90-day curing age (Table 28).

Table 28 | Average densities of sludge ash-amended concrete blocks

Mix ID	**Sludge ashes (% wt of cement)**	**Average density (g/cm^3)**		
		Curing age: 7 days	**Curing age: 28 days**	**Curing age: 90 days**
M20-00A-ADD	Control (0%)	2.398	2.420	2.428
M20-10A-ADD	10%	2.380	2.402	2.386
M20-20A-ADD	20%	2.361	2.355	2.379
M20-30A-ADD	30%	2.337	2.350	2.346

It should be noted that the density parameter is not a direct measure of the permeability of concrete. Typically, high permeability-concrete is not desirable as it increases the infusion of water moisture into the concrete microstructure. This could lead to accelerated deterioration of the concrete as the sulfates and chlorides in the moisture attack the hydrated cement.

4.6 Biosolids and biosolids ashes as partial replacement for fine aggregates

The results in the previous section indicated that the addition of as much as 10% of biosolids ashes to a concrete mix did not affect the general physical properties (strength, water absorption, density, and workability) of cured concrete blocks. On the other hand, the addition of an equal quantity of dried biosolids decreased the compressive strength of concrete by about 15 – 20% which is unacceptable since the acceptable value established in section 3 is 10% only.

Theoretically, adding either biosolids or biosolids ashes (in large quantities) to concrete mixture essentially displaces equal portions of all the mixture ingredients including cement. As a result, part of the cement is lost – thus contributing to further reduction in strength.

In order to avoid the replacement of cement by the biosolids and biosolids ashes, a trial test is carried out for one grade of concrete (M20) using dried biosolids and biosolids ashes as sand (fine aggregate) replacement. The selected percentages are: 10% biosolids ashes, and a combination of 2.5% biosolids + 7.5% sludge ashes.

4.6.1 Compressive strength

Table 29 shows the results obtained for the compressive strength of concrete specimens by:

i. replacing sand with 10% sludge ashes (measured by weight of sand)
ii. replacing sand with a combination of 2.5% dried biosolids and 7.5% sludge ashes (measured by weight of sand)

Table 29 | Compressive strength of grade M20 concrete as a function of biosolids added as a sand replacement

Test ID	% weight of sand		Concrete Grade	Average compressive strength (MPa)		
	Dried solids	Biosolids ashes		Age: 7 days	Age: 28 days	Age: 90 days
M20-00A-REP	0%	0%	M20	19.42	23.87	27.32
M20-00A-REP	0%	10%	M20	18.93	24.11	26.81
M20-75A25B-REP	2.5%	7.5%	M20	19.77	22.19	26.08

Results from Table 29 and Figure 40 illustrate that there is no significant change in the relative strengths of the tested concrete blocks when sludge ashes is used in small quantities (i.e. 10%) as sand replacement in the concrete mixture.

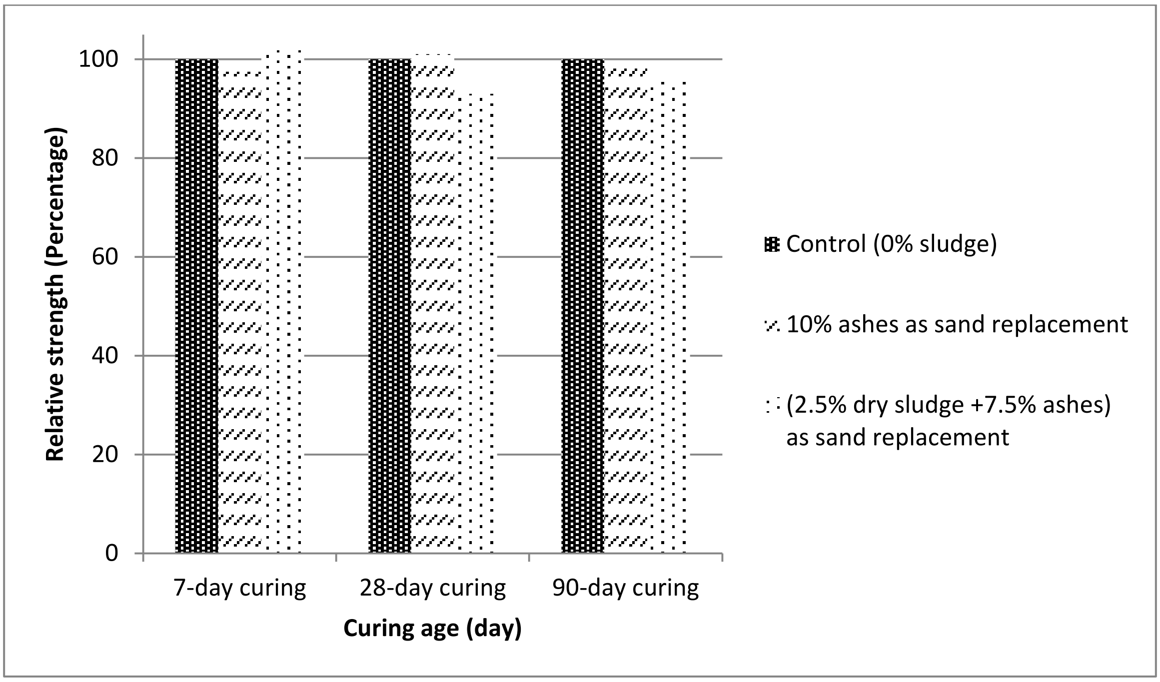

Figure 40 | Relative strength of concrete as a function of sludge as sand repalcement

Replacing sand with a mixture of 2.5% dry sludge and 7.5% sludge ashes, does not alter the relative compressive strength at day 7, but slightly reduces it on days 28 and 90. This reduction in the load bearing capacity can be attributed to the presence of organic matter in the dried sludge that was added to the concrete mixture.

4.6.2 Slump

Results in Table 30 show that there a slight but insignificant decrease in slump values when replacing sand with sludge ash and also when replacing sand with a combination of dry sludge and ashes.

Table 30 | Slump values for sand replacement experimentation program

Test ID	% weight of sand		Concrete Grade	Slump (mm)
	Dried solids	Biosolids ashes		
M20-00A-REP	0%	0%	M20	7.2
M20-00A-REP	0%	10%	M20	6.8
M20-75A25B-REP	2.5%	7.5%	M20	7.0

4.6.3 Density and water absorption

Table 33 and 32 show the average density and average water absorption values of sludge-amended bricks in which sludge was added in one specimen as 10% as dried biosolids and in another specimen as a combination of 2.5% dried biosolids and 7.5% sludge ashes.

The densities of the produced blocks are not significantly affected when measured at the 7, 28, and 90-day curing ages. This is expected since the amounts of the sludge and sludge ashes added are small.

Table 31 | Density results for sludge-amended concrete blocks (sludge as sand replacement)

Mix ID	(% wt of sand)		Average density (g/cm^3)		
	Dried solids	Biosolids ashes	7 days	28 days	90 days
M20-00A-REP	0%	0%	2.398	2.420	2.428
M20-00A-REP	0%	10%	2.450	2.480	2.390
M20-75A25B-REP	2.5%	7.5%	2.364	2.490	2.475

Table 32 | Water absorption values for sludge-amended concrete blocks

Mix ID	(% wt of sand)		Average water absorption @ a curing age of 28 days
	Dried solids	Biosolids ashes	
M20-00A-REP	0%	0%	4.22%
M20-00A-REP	0%	10%	5.80%
M20-75A25B-REP	2.5%	7.5%	5.80%

Water absorption values indicate a slight increase in the absorption capacity of the blocks that contain sludge and ashes.

4.7 Evaluation of economic savings

The rapid growth of the construction sector, population growth, and demographic changes (moving of people from rural areas into cities) have contributed to an increase in demand for building materials – particularly cement. As a matter of fact, cement in the form of concrete is the most used building material on earth. The West Bank consumes about 2 million tons of cement annually (PECDAR, 2007).

This section outlines the results of the economic savings in production costs that can be achieved by the manufactures of masonry bricks.

As reported by bricks factory owners, the most commonly used and sold brick in the West Bank is a masonry concrete unit of 40 cm x 20 cm x 10 cm. Table 33 summarizes the average retail prices of CMUs of different sizes as reported by concrete business owners. Prices were collected from personal visits and phone calls to factories across the West Bank.

Table 33 | Average retail sale prices of concrete masonry units as reported by business owners

CMU dimensions (cm)	Average sales price range (NIS/CMU)
40 x 20 x 10	1.5
40 x 20 x 7	1.3
40 x 20 x 15	2.3
40 x 20 x 4	1.5
40 x 22 x 17	2.6
40 x 20 x 30	3.4
50 x 20 x 6	3.2

The cost analysis throughout this section is based on the most commonly produced brick. The typical manufacturing cycle of the bricks is short, generally taking less than 2 weeks – from the mixing of raw materials stage, all the way to the moist curing. For existing businesses, the production costs of each brick entails labor, utilities (water and electricity), raw materials (cement, sand, crushed stone), machinery maintenance, and management expenses. The transport costs of the bricks from the factory to the construction location are usually paid by the customer. Bricks are not heat treated, and hence the most prominent single production expense is the cost of cement which is about 420 NIS/ton.

Table 34 shows the breakdown of the production cost of 40 x 20 x 10 cm concrete masonry bricks for a typical factory with an average production rate of 6,000 CMUs per day. From the results, each brick sale brings in a net profit of about 0.70 NIS.

Table 34 | Typical CMU production cost in the West Bank

Average Operational Costs	Unit	Unit Cost NIS	Total Cost NIS
Labor Costs	**5 Persons**	**2,000**	**10,000**
Electricity	**Lump sum**	**2,500**	**2,500**
Water	**Lump sum**	**1,500**	**1,500**
Machinery	**Lump sum**	**1,000**	**1,000**
Management expenses	**Lump sum**	**6,500**	**6,500**
Raw Materials	Metric Tons	Unit Cost NIS/ton	Total Cost NIS
Portland 250 (Origin: Israel)	**96**	**420**	**40,320**
Sand (FA)	**240**	**75**	**18,000**
Crushed stone (CA)	**480**	**25**	**12,000**
Water[1]	**---**	**---**	**---**
Production rate [2]	Brick	Unit Cost NIS/CMU[3]	
Brick size: 40 x 20 x 10 cm Bearing capacity: 6 MPa[4] C:FA:CA = 1.2:3:6 Typical sale price: 1.50 NIS[6]	**120,000/month**	**0.765**[5]	

(1) Price is included as part of the operational costs
(2) Based on 5 day/week operation
(3) Concrete masonry unit
(4) Laboratory tested and exceeds ASTM specifications of 3.5 MPa
(5) Calculation is based on data in table. 1 NIS = 0.278 USD
(6) 14.5% VAT included. Not including transportation to customer

Table 35 shows that the reduced production costs can be attributed to the use of less quantity of raw materials.

Table 35 | Comparative analysis of CMUs production cost with and without adding sludge[1]

Sludge percentage	0% No Sludge Addition	10% ashes as mixture additive	2.5% solids and 7.5% ashes as partial sand replacement	10% ashes as partial sand replacement
Raw Materials				
Cement (NIS/10 CMUs)	3.36	3.32	3.35	3.36
Sand (NIS/10 CMUs)	1.50	1.48	1.45	1.35
Crushed stone (NIS/10 CMUs)	1.00	0.988	1.00	1.00
Water (NIS/10 CMUs)	---	`		
Operational Costs				
Labor costs	0.83	0.83	0.83	0.83
Electricity	0.21	0.21	0.21	0.21
Water	0.13	0.13	0.13	0.13
Machinery	0.08	0.08	0.08	0.08
Management Expenses	0.54	0.54	0.54	0.54
Total NIS/10 CMUs	**7.65**	**7.58**	**7.59**	**7.50**
Monthly Savings (NIS)	--	**864**	**720**	**1,800**

(1) Factories are assumed to receive the sludge/ashes ready to be incorporated into cement mixture

When adding 10% sewage sludge ashes to the concrete mixture, the ashes are occupying and replacing a small volume of all the raw materials. Assuming the each of the raw materials is being displaced by a quantity of biosolids that is equal to the ratio that the material is present in the mixture, then the cost savings would be around 864 NIS per month. The highest savings that can be achieved are when biosolids was incorporated in the concrete mixture as a partial replacement for sand. In this case, the monthly cost savings were 1,800 NIS.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The most feasible management options for biosolids are those that accommodate local conditions and circumstances, provide maximum beneficial uses of the biosolids, and satisfy a wide range of success criteria including health and environmental risks, reliability, public support, and cost.

New and emerging technologies are not changing the overall picture of biosolids management for local communities and municipalities in any new or significant way but are useful because they question all current sludge management assumptions and attempt to draw attention to the fact that biosolids can be used in one way or another and is *not* something that is being discarded anymore – it can be a valuable resource.

In the wastewater treatment domain, researchers and engineers have long strived to design and optimize wastewater treatment technologies that are efficient in treating sewage but that generate as little sludge as possible as a byproduct. However, if sewage sludge is to be considered as a marketable product, and given that this product will be in high demand, then, wastewater treatment plants should be engineered so as to increase and optimize their biosolids production.

5.2 Conclusions

Stabilized sewage sludge (biosolids) and sludge ashes cannot replace the cement constituent of a typical concrete mixture as neither of them contain the binding agents that are present in cement. However, biosolids and sludge ashes can be added in limited quantities as additives or as sand replacement to a typical concrete mixture without having considerable negative effects on the structural integrity of the cured concrete.

- Despite the fact that biosolids were sun-dried for 2 weeks, their high organic content negatively affected the early age and final compressive strength development of the cured concrete cubes. The lowest negative effect was a 13%

compressive strength decrease when 10% dried sewage sludge was incorporated into the concrete mixture. The maximum damaging effect occurred when adding 30% dried biosolids that resulted in a 40% decrease in the load bearing capacity of concrete.

- The addition of incinerated sewage sludge ashes to the raw material concrete mixture in small quantities (i.e. no more than 10%) had no significant negative effect on the compressive strengths of the cured blocks recorded on the 7th and 28th days of the curing age. The compressive strength at day 90 showed a 4% decrease.

- Working with concrete paste mixtures of acceptable workability is critical to the efficiency of the bricks production process. Mixtures of low slump values can cause frequent machine clogging while those of high slump values can affect compaction and molding of the concrete blocks. Incorporating sun-dried biosolids in large quantities (i.e. 30%) into the concrete mixture paste resulted in water-reducing effects and hence decreased slump values. On the other hand, slump values of concrete pastes having sewage sludge and sludge ashes in quantities of up to 10% are not significantly affected and are well within the acceptable range of typical concrete mixes.

- Low water absorption capacity is one of the most important properties of good quality of concrete bricks. With the exception of concrete blocks containing 30% dried sewage sludge, the water absorption capacities of were below the maximum limit specified by ASTM C90.

- As long as it meets the desired strength criteria, low-density concrete is desirable in many construction applications. The density of the cured concrete blocks decreased with the increase of the quantity of biosolids and ashes that were incorporated into the blocks which can be attributed to the increase in porosity of the cured concrete.

- When dried sludge and sludge ashes are used in small quantities to replace sand in the concrete mixture, there was no significant negative effect on the workability of the concrete paste and on the compressive strength development, water absorption, and density of the cured blocks.

- The most economic option for producing bricks that are amended with biosolids, is to use incinerated sewage sludge ashes as a partial replacement for the sand in the raw material mix-design. Using 10% sewage sludge ashes as a partial sand replacement can cut raw material cost by up to 15%.

5.3 Recommendations

- The hydration chemistry of sewage sludge and sewage sludge ashes should be investigated and compared to the pozzolanic reactions of cementitious products such as cement so as to better understand if ashes could be used to augment the strength development of concrete.

- There is a need for an enlightened government policy to drive supply and demand for cleaner production and green technologies. Lower taxes, tax credits, and subsidies could be possible key drivers that may be used to stimulate the marketplace and create a wide customer base to absorb greener production technologies and to drive the innovative use of bio-solids in the construction industry further.

- There is a need for the development of local rules defining bio-solids quality, classification, and disposal. Palestinian regulatory authorities can capitalize on the regulations developed in the United States based on performance standards of the two classes of pathogen reduction (United States Federal Register, 1993).

5.4 Lessons learned

- Many of the ASTM specifications that regulate concrete production explicitly do not allow the use of new materials in the production of concrete. As an example, ASTM C-331 specifies that lightweight masonry concrete units (CMUs) shall use lightweight aggregates of expanded clay, expanded shale, volcanic cinders, pumice, or a combination thereof. In other words, ashes cannot be used as lightweight aggregates in the manufacture CMUs.

- Recognizing the existence of a biosolids' disposal challenge is only halfway to winning the bisolids management battle. Getting the whole ecosystem to respond – from local councils to cities to regulating authorities and from the public sector to the private sector – is another matter. Therefore, in addition to finding feasible technologies, mitigating the hazards posed by the ever increase in bio-solids production rates, requires a combination of both social and political willpower.

- The technology of producing building bricks with bio-solids as a partial or full raw material substitute has reached the piloting and developmental stages overseas and has even been successfully demonstrated at a full-scale level in Japan. However, the technology is still in the embryonic and bench-scale levels in the Europe, USA, and the Middle East.

- For cost-cutting purposes, a few concrete production facilities in the West Bank are not using sand in their concrete mixture. Instead, they are utilizing finely-crushed limestone (passing a 6 mm sieve) as a sand replacement. In this case, the cost savings is only applicable when using sludge as an additive and not as a sand replacement.

- The production of excellent quality bio-solids at reduced prices – that is suitable to be recycled and re-used, requires innovative and case-specific solutions that go beyond the wastewater treatment plant but also addresses the quality of domestic, commercial, and industrial discharges into the municipal sewers.

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APPENDICES

Appendix I

Concrete Mix Design Procedure

Sample Calculation

(IS 10262:2009 Method)

Concrete Mix Design Procedure (IS 10262:2009 method)

Control Sample Calculation:

A well proportioned concrete mix should posses the acceptable workability of freshly mixed concrete paste; durability, strength, uniform appearance of hardened concrete; and economy.

The procedure of mix design determines the unit proportions (volume and weight) of concrete mix constituents (cement, aggregates, and water) of a pre-defined concrete grade. Following are the specifications that are to be used as per field data obtained from concrete makers in Palestine:

Concrete grade	M20
Cement Type	Type I all-purpose cement (Sp. Gravity: 3.2)
Minimum cementing material content	320 kg/m^3 (for durability purposes)
Maximum water to cement ratio (w/c)	0.70
Maximum nominal size of aggregates	20.0 mm
Aggregate type	Crushed (angular)
Slump (workability)	75 m

I. Target Mean Strength (TMS) for mix proportioning

In order to calculate the mix proportions of M20 grade concrete, the target mean strength has to be calculated.

The first step was to choose a required concrete strength

$\mathbf{F_t = F_{cs} + k \cdot s}$

where

F_t target mean strength
F_{cs} characteristic strength (design strength) @ a curing age of 28 days
k appropriate value to the defect percentage permitted below the characteristic strength
s standard deviation of the particular mix

Table 36 | Concrete grade designation according to its characteristic compressive strength

Grade designation	Specified characteristic compressive strength (MPa) @ a curing age of 28 days	Standard deviation, s N/mm^2
M10	10	3.0
M15	15	3.5
M20	20	4.0
M25	25	4.0
M30	30	5.0
M35	35	5.0
M40	40	5.0

M45	45	5.0
M50	50	---
M55	55	---
M60	60	---

Table 37 | Relationship between to cementitious material ratio and compressive strength of concrete

Compressive strength Moist-cured concrete @ 28 days, MPa	Water-cementitious materials ratio by mass (w/c)	
	Non-air-entrained concrete	Air-entrained concrete
45	0.38	0.30
40	0.42	0.34
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

Relationship assumes nominal maximum size aggregate of 19-25 mm

From Table 38, the statistical constant k is determined to be 1.65 at 5% defect percentage.

Table 38 | Statistical constant k as a function of permitted defect percentage permitted

Percentage of result below the characteristic strength	20%	10%	5%	2.5%	1.0%
k	0.84	1.28	1.65	1.96	2.33

Using the standard deviation (Table 36) for concrete of grade M20, then:Ft = 25 + 1.65 x 4.0 = 31.6 N/mm^2

II. Water-Cement Ratio (W/C)

Using Table **37**, a water to cement ratio of 0.52 is selected

[Constraint check: 0.52 < 0.70 hence it is okay].

Using Table 39 and Figure 41, the estimated mixing water quantity = 202 $liters/m^3$ (for 75 mm – 100 mm slump range and 20 mm aggregate size)

Table 39 | Estimated water mixing requirements and air content requirements for different slumps and aggregate sizes

	Aggregate size (mm)							
	9.5	**12.5**	**19**	**25**	**37.5**	**50**	**75**	**100**
Non-air-entrained								
Slump (mm)	Mixing water quantity (Kg/m^3)							
25-50	207	199	190	179	166	154	130	113
75-100	228	216	205	193	181	169	145	124
150-175	243	228	216	202	190	178	160	---
Typical entrapped air (percent)	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained								

Slump (mm)	Mixing water quantity (Kg/m^3)							
25-50	181	175	168	160	148	142	122	107
75-100	202	193	184	175	165	157	133	119
150-175	216	205	197	184	174	166	154	---
Recommended air content (percent)								
Mild Exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate Exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe Exposure	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0

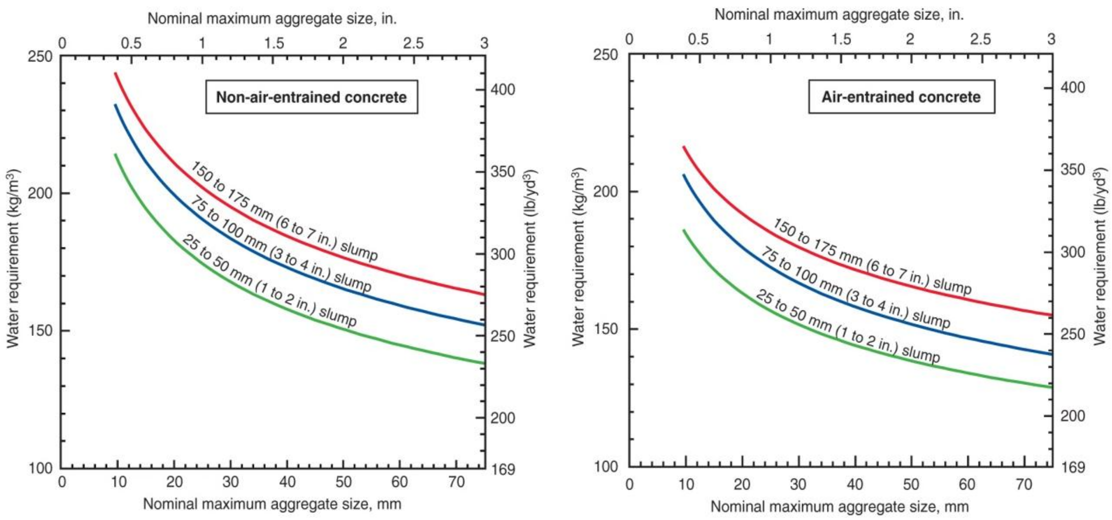

Figure 41 | Estimated water requirement for various slumps and crushed aggregate sizes

Water-cement ratio (w/c) = 0.52

Therefore, cement content = 201 liters/m^3/0.52

= 386.54 kg/m^3

[Constraint check: 386.54 kg/m^3 > 320 kg/m^3, hence ok]

III. Aggregate content calculations

Aggregate grading (particle size and distribution) have an important influence on concrete proportioning mixture because they affect the workability of fresh concrete. Further, grading is critical for creating an economical mixture because it directly affects the amount and volume of concrete that can be made with a given amount of cement (Kosmatka, Kerkhoff, & Panarese, 2008).

Based on empirical data, the American Concrete Institute recommends that the percentage (by unit volume) of coarse aggregate to be based on the nominal maximum aggregate size and fine aggregate fineness modulus. An increase in recommended values by 10% is allowed for pavement concrete.

Table 40 | Estimated volume of coarse aggregate (per unit volume of PCC) for different fine aggregate fineness moduli and different nominal maximum aggregate sizes

Nominal maximum (coarse) aggregate size	Fine aggregate fineness modulus			
	2.40	**2.60**	**2.80**	**3.00**
9.5 mm	0.50	0.48	0.46	0.44
12.5 mm	0.59	0.57	0.55	0.53
19 mm	0.66	0.64	0.62	0.60
25 mm	0.71	0.69	0.67	0.65
37.5 mm	0.75	0.73	0.71	0.69
50 mm	0.78	0.76	0.74	0.72

Using Table 40, the volume of coarse aggregate corresponding to a 20 mm size aggregate is 0.66 for every unit volume of PCC.

In order to determine the fineness modulus of fine aggregates, a weighed sample of oven-dried fine aggregate is separated through a series of sieves of progressively smaller openings. The standard test method ASTM C136 was used in the laboratory for sieve analysis to determine the particle size distribution of fine aggregates (i.e. sand), and are shown in Table 41. The fine aggregate used in this work meets the ASTM C33 specifications as can be seen in Figure 42 below.

Generally, the fineness modulus of sand varies from 2.0 to 4.0. The higher the FM, the coarser the sand is:

Sand Type	**Fineness Modulus (FM)**
Fine	2.0 to 2.8
Medium	2.8 to 3.2
Coarse	3.2 to 4.0

In this study, the fine aggregate is a combination of sand and crushed stone. Their combined sieve analysis is shown in Table 41.

Table 41 | Laboratory sieve analysis of fine aggregate with maximum size of 2.36 mm

Opening size	Cumulative weight of sand retained	Cumulative percentage of sand retained	Percentage of fine aggregates passing	Percentage of fine aggregates retained	ASTM C33 Requirement (passing)	
					Low	High
(mm)	(g)	%	%	%	%	%
9.5	0.0	0.0	100	0.0	100	100
4.75	0.0	0.0	100	0.0	95	100
2.36	37.0	7.4	92.6	7.4	80	100
1.18	142.5	35.9	71.5	28.5	50	85
0.6	201.5	76.2	59.7	40.3	25	60
0.3	354.0	147.0	29.2	70.8	10	30

0.15	474.5	241.0	5.1	94.9	2	10
<0.15	499.0	---	0.2	99.8	---	---
Fineness Modulus				2.42		

Dry weight of original sample is 500.0 g. Sample was oven-dried at 110 ± 5 °C

The F.M. = Σ{(Cumulative % retained on #4, 8, 16, 30, 50, 100 sieves)/100}

F.M.of fine aggregate = (0+7.4+28.5+40.3+70.8+94.9)/100 = 2.42

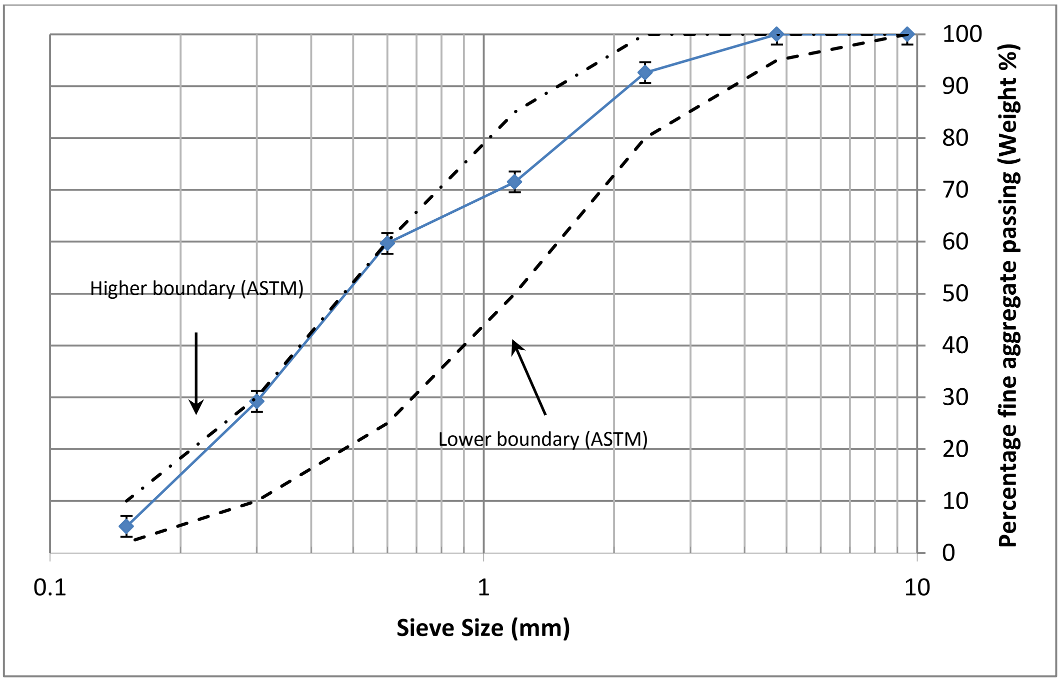

Figure 42 | Graphical representation of the laboratory sieve analysis of fine aggregate using ASTM C136

Figure 42 indicates that the sieve analysis carried out in the testing laboratory is in compliance with the minimum and maximum ranges as specified by ASTM C136.

IV. Weight proportion calculations

Volume of concrete cube = 1 m^3

Volume of cement = mass/sp. gravity = 386.54 kg/m^3/3.2/1000 = 0.121 m^3

Volume of mixing water = 202 Kg/m^3/1/1000 = 0.202 m^3

Volume of coarse aggregates + fine aggregates = 1 – (0.121 + 0.202) = 0.677 m^3

Volume of coarse aggregates = 0.677 m^3 x 0.66 = 0.447 m^3

Mass of coarse aggregates = volume x sp. gravity = 0.447 x 2.68 x 1000 = 1197.4 Kg/m^3

Volume of fine aggregates = 0.677 m^3 x 0.34 = 0.230 m^3

Mass of fine aggregates = 0.230 m^3 x 2.65 x 1000 = 610.0 Kg/m^3

Resultant mix proportions for Mix 1 for every standard-size 10 mm x 10 mm x 10 mm concrete cube :

Cement =	386.54 g
Fine aggregate =	610.0 g
Coarse aggregate =	1197.4 g
Water =	202 ml
Water/Cement Ratio =	0.52
C:FA:CA ratio ≈	1:1.5:3
Total mix weight =	2395.94 g

Appendix II

Estimation of Biosolids production in Palestine

(Based on BOD laboratory tests and influent rates obtained from Al-Bireh Municipality)

The bio-solids production rate in Palestine can be calculated based on an estimate of observed solids yield data from similar facilities combined with data collected at a major wastewater treatment plant as shown in equation below (Asano, 2007) and the figure below.

The observed yield decreases as the solids retention time (SRT) is increased because of the resultant biomass loss due to increased indigenous respiration especially at higher temperatures.

$$P_{X,VSS} = Y_{obs}(Q)(S_o - S)(1\ Kg/10^3\ g) \qquad \text{Equation (1)}$$

$P_{X,VSS}$ = net waste activated sludge produced per day, Kg VSS/d
Y_{obs} = observed yield, g VSS/g substrate removed
Q = influent flow, m^3/d
S_o = influent substrate concentration, g/m^3 (mg/L)
S = effluent substrate concentration, g/m^3 (mg/L)

Assumptions:

Population:	4,043,218
Population growth:	2.25%
SRT:	10 days
Temperature:	20 °C
Average daily inflow:	5000 m^3/d
Average influent substrate concentration:	440 mg/L
Average outflow substrate concentration:	10 mg/L

The observed volatile suspended solids (VSS) yield value based on BOD is determined from the figure below which is 0.65 Kg VSS/Kg BOD

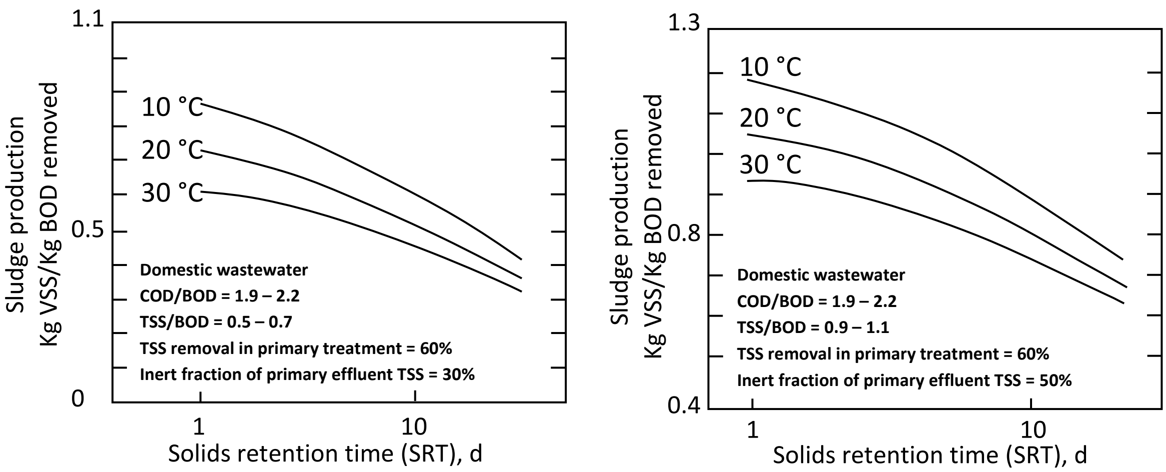

Figure 43 | Net solids production versus solids retention time (SRT) and temperature: (a) with primary treatment and (b) without primary treatment (Asano, 2007)

Therefore,

(0.55 Kg VSS/Kg BOD) x (5000 m^3/day) x (440 – 10 mg/L) ≈ 1200 Kg/day

Appendix III
Compressive strength sample calculation

(Based on standard cubes of 10 x 10 x 10 cm and a constant loading rate of 0.63 MPa/s)

Control specimen (M20SD00):

Number of cubes: **3**

Curing age: **7 days**

Biosolids percentage: **0%**

Size of the each cube: **10 cm x 10 cm x 10 cm**

Area of the specimen: **100 cm^2**

Load for M20SD00-1: 199.4 Kg/cm^2 = 19.55 MPa = 2835 psi
Load for M20SD00-2: 195.9 Kg/cm^2 = 19.21 MPa = 2786 psi
Load for M20SD00-3: 198.8 Kg/cm^2 = 19.50 MPa = 2828 psi

Average: (3593 + 3622 + 3604)/3 = 3606 psi

Cube #	Curing age	Characteristic compressive strength (MPa)
M20SD00 -1	7	19.55
M20SD00 -2	7	19.21
M20SD00 -3	7	19.50
Average		**19.42**

{Constraint check: if any of the cubes deviates more than 10% of the average (i.e. 2816 psi)]

Calculate 10% of 2816 = 282 psi

Cube M20SD00-1: 2835 - 2816 = 19 psi < 282 therefore ok.
Cube M20SD00-2: 2816 – 2786 = 30 psi < 282 therefore ok.
Cube M20SD00-3: 2828 – 2816 = 12 psi < 282 therefore ok.

Average compressive strength @ 7 days of curing age: 2816 psi = 19.42 MPa

Appendix IV
Control Samples Detailed Results

CONTROL SAMPLES

Mix design proportions:

Grade	Weight of mix components (g)				Total Weight (g)	Ratios	
	Water	Cement	Coarse Aggregate	Fine Aggregate		w/c	C:FA:CA
M20	201	386.5	1199.6	611.1	2398.2	0.52	1:1.6:3.1
M25	201	446.7	1166.3	594.1	2408.2	0.45	1:1.3:2.6
M30	201	515.4	1128.4	574.8	2419.6	0.39	1:1:2

Compressive strength & density:

7-day curing age

Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M20-1	10 x 10 cm = 100 cm^2	0.63	2835	19.55	2.409
M20-2	10 x 10 cm = 100 cm^2	0.63	2786	19.21	2.389
M20-3	10 x 10 cm = 100 cm^2	0.63	2828	19.50	2.396
Average			**2816**	**19.42**	**2.398**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M25-1	10 x 10 cm = 100 cm^2	0.63	3616	24.93	2.418
M25-2	10 x 10 cm = 100 cm^2	0.63	3577	24.66	2.390
M25-3	10 x 10 cm = 100 cm^2	0.63	3629	25.02	2.419
Average			**3607**	**24.87**	**2.409**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M30-1	10 x 10 cm = 100 cm^2	0.63	4203	28.98	2.429
M30-2	10 x 10 cm = 100 cm^2	0.63	4184	28.85	2.415
M30-3	10 x 10 cm = 100 cm^2	0.63	4195	28.93	2.419
Average			**4194**	**28.92**	**2.421**

28-day curing age

Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M20-1	10 x 10 cm = 100 cm^2	0.63	3477	23.97	2.430
M20-2	10 x 10 cm = 100 cm^2	0.63	3451	23.79	2.425
M20-3	10 x 10 cm = 100 cm^2	0.63	3458	23.84	2.405

Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
Average			**3462**	**23.87**	**2.420**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M25-1	10 x 10 cm = 100 cm^2	0.63	4473	30.84	2.410
M25-2	10 x 10 cm = 100 cm^2	0.63	4461	30.76	2.399
M25-3	10 x 10 cm = 100 cm^2	0.63	4452	30.70	2.385
Average			**4462**	**30.77**	**2.398**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M30-1	10 x 10 cm = 100 cm^2	0.63	5603	38.63	2.415
M30-2	10 x 10 cm = 100 cm^2	0.63	5624	38,78	2.419
M30-3	10 x 10 cm = 100 cm^2	0.63	5630	38.82	2.381
Average			**5619**	**38.74**	**2.405**

90-day curing age

Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M20-1	10 x 10 cm = 100 cm^2	0.63	3977	27.42	2.408
M20-2	10 x 10 cm = 100 cm^2	0.63	3969	27.37	2.411
M20-3	10 x 10 cm = 100 cm^2	0.63	3940	27.17	2.465
Average			**3962**	**27.32**	**2.428**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M25-1	10 x 10 cm = 100 cm^2	0.63	5602	38.62	2.406
M25-2	10 x 10 cm = 100 cm^2	0.63	5587	38.52	2.428
M25-3	10 x 10 cm = 100 cm^2	0.63	5593	38.56	2.432
Average			**5594**	**38.57**	**2.422**
Grade-Sample#	Axial Area	Loading rate (MPa/s)	Compressive Strength		Density (g/cm^3)
			psi	MPa	
M30-1	10 x 10 cm = 100 cm^2	0.63	6570	45.30	2.422
M30-2	10 x 10 cm = 100 cm^2	0.63	6599	45.50	2.440
M30-3	10 x 10 cm = 100 cm^2	0.63	6586	45.41	2.431
Average			**6585**	**45.40**	**2.431**

Workability of the concrete mix:

Grade Sample #	Workability (mm)
M20-1	73
M20-2	71
M20-3	72
Average	**72**
M25-1	69
M25-2	70
M25-3	71
Average	**70**
M30-1	70
M30-2	71
M30-3	69
Average	**70**

Water absorption @ 28 days of curing age:

Grade Sample #	Dry Weight (g)	Wet Weight (g)	Weight Increase (g)	Absorption Percentage (%)
M20-1	2430	2537	107	4.40
M20-2	2425	2530	105	4.32
M20-3	2405	2507	102	4.24
Average				**4.32**
Grade Sample #	Dry Weight (g)	Wet Weight (g)	Weight Increase (g)	Absorption Percentage (%)
M25-1	2410	2523	113	4.70
M25-2	2399	2511	112	4.65
M25-3	2398	2516	118	4.90
Average				**4.75**
Grade Sample #	Dry Weight (g)	Wet Weight (g)	Weight Increase (g)	Absorption Percentage (%)
M30-1	2415	2526	111	4.60
M30-2	2425	2534	109	4.50
M30-3	2381	2486	105	4.40
Average				**4.50**

Appendix V

Survey Questions to Establish Economic Study

جامعة بيرزيت – استبيان حول مصانع الطوب الإسمنتي

١- القدرة الإنتاجية للمصنع (عدد الطوب المنتج في اليوم/الأسبوع/الشهر).

٢- عدد العاملين في المصنع (عمّال وفنيين).

٣- متوسط الراتب اليومي/الشهري للعامل/الفني الواحد.

٤- معدّل قيمة فاتورة الكهرباء الشهرية للمصنع.

٥- سعر شراء الإسمنت للطن الواحد مع تحديد النوعية/المصدر.

٦- سعر شراء الحصمة للطن الواحد.

٧- سعر شراء الرمل للطن الواحد.

٨- نوع ومواصفات الطوب الأكثر مبيعاً (طول –عرض – ارتفاع) – قوة تحمل الضغط

٩- سعر المبيع للطوبة الواحدة (أو متر الطوب)

١٠- معدّل قيمة فاتورة الماء في الشهر الواحد.

١١- كمية الطوب المنتج من كل ١ طن اسمنت مع تحديد أبعاد الطوبة.

١٢- نسب المواد الأولية المستخدمة في صنعاة الطوب.
